AMERICAN UNIVERSITY OF BEIRUT

A LOCATION BASED APPROACH TO STUDY THE IMPACT OF CONSTRUCTION LOGISTICS AND PRODUCTION CONTROL ON CREW PERFORMANCE

by
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AN ABSTRACT OF THE THESIS OF

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Construction logistics and production control can enhance project performance. Several techniques can be applied to these systems, each having different effects on project performance. Push planning and pull planning have been studied and implemented to these systems; push planning mainly uses end dates to control the project, whereas pull planning pulls from milestones and the state of the system. Researchers have been studying and contrasting the mentioned approaches from scheduling and control perspectives trying to improve project performance, mainly considering tasks and project durations. However, zooming into the level of crews and locations within a project, it is noticed that the effect of the mentioned production control approaches on crew performance including labor productivity, crew allocation to areas, idle time, and other crew performance metrics still need to be studied.

This research reviews onsite construction logistics and production control techniques, studies them at the level of locations, and proposes hypotheses relating push and pull production control techniques to several project and crew performance metrics. The significance of this study is materialized in two main contributions. First, the study contrasted push and pull planning techniques at the level of locations, and second, it exposed the effects of push and pull planning on crew performance including labour productivity and other project performance metrics. This enabled a convergence to generalized conclusions regarding optimum methods to deal with different production control issues.

Agent-based modelling is used to develop a simulation model that describes how each of push and pull production control techniques affects crew performance. The model depicts crews' interactions and allocation to tasks within the project locations. During simulation, several metrics indicating the performance of crews, activities, and the project were measured and stored. After conducting several runs to accumulate enough data, the collected data was used to test several hypotheses concerning push and pull production control techniques and their effects on crews and project performance.

Pull planning resulted in higher productivity, shorter idle time, less crew turnover and task interruptions, however, it showed an increase in project duration. Analyzing the mentioned results besides other performance metrics drew a main conclusion that push and pull techniques should be applied together to reach a representative and flexible production control system.

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CHAPTER 1

INTRODUCTION

Construction industry may be considered as one of the most complex industrial practices. The level of complexity is defined by how complicated the management issues are (Bennett, 1991). Thus, the need to complete a construction project efficiently requires consistent management at various levels (Guffond & Leconte, 2000). Construction management may be defined as a system that "addresses how the resources available to the manager can be best applied." These resources mainly include manpower, equipment, materials, and money (Halpin, 2010). This research addresses parts of construction management, which are pull and push production control and construction logistics, to study their impact on crew performance.

Traditional "production planning and control" is a management practice to reduce variations from schedules and budgets; it tries to manage schedules reactively. This traditional practice creates a "contract-minded culture", as it increases waste and variability (Hamzeh, 2009). To better manage production in construction industry, lean construction principles are applied, whereby value in the eyes of the customer is maximized, waste is reduced, and workflow becomes more reliable (Howell & Ballard, 1998).

Moreover, in order to improve planning and production performance, a research concentration under lean construction was developed, which is the Last Planner System (LPS), that aims to reducing variability and its negative impacts, and increasing workflow reliability (Ballard, Hamzeh, & Tommelein, 2007; Ballard & Howell, 1994; Tommelein & Ballard, 1997).

LPS breaks down activities from phases to processes then to operations through four planning processes: master scheduling, phase scheduling, lookahead planning, and weekly work planning. Master scheduling mainly sets project-level activities and project milestone dates. Then in phase scheduling, project phases are broken down into activities that are scheduled backward from the milestones (activities are pulled from milestones). Lookahead planning usually covers six-week schedules, where activities are broken down into operations that are made ready through removing their constraints. Finally, weekly work planning represent the most detailed plan in the system where it directly drives the production process (F. Hamzeh, Ballard, & Tommelein, 2012). Pull mechanism is applied in these processes, whereby tasks are pulled from milestones and completed based on the need of these tasks downstream. The pull technique is also applied in Location Based Management System (LBMS) that will be described in the literature review section. This happens unlike the traditional push mechanism where tasks passively wait until all their prerequisites and resources are available (Tommelein & Ballard, 1997).

Moving to construction logistics management, it may be defined as the management of the process of delivering materials and resources required at a construction site in a productive way (Guffond & Leconte, 2000). It is not only the management of the flow of material and information (Tixier, Mathe, & Colin, 1998), it includes as well delivering quality, ensuring safety, and providing an environment that facilitates construction activities (Fabbe-Costes, 1997).

Considering material management, it can be noticed that material tracking and process optimization happen at various levels covering production, warehousing, and delivery process, but stop when materials arrive to construction sites considering that materials have reached their final destination. Yet, looking through the eyes of crews on site, material arrival to site does not mean that materials are in the right place. Crews still need to procure materials to the workplaces where they are installed/used.

As for production control, it is noticed that push technique, which sticks to the schedule during project execution and uses end dates to control a project, has been applied in traditional project planning and control systems including CPM. Besides, pull techniques are studied and applied in LBMS and LPS, through pulling from milestones and based on the state of the system. Moreover, push planning has been compared to pull planning from scheduling and control perspectives, but what is still missing is the effect of pull and push techniques on crew productivity, crew allocation to areas, and the crew movement at the level of locations/workplaces on the project.

Therefore, this paper reviews production planning and control systems, studies push planning and pull planning at the level of locations, and addresses the effect of these techniques on labor productivity, crew logistics/allocation to areas, crew movement, and crews' interactions within a project. These objectives are addressed through agent-based modeling and simulation of push and pull production planning scenarios, while measuring several performance metrics that help in the contrasting between these techniques, reaching optimal approaches and recommendations.

CHAPTER 2

BACKGROUND RESEARCH

This chapter presents the literature review supporting this research. It will first discuss site material management, then production planning and control systems.

A. Site Material Management

Construction logistics includes offsite and onsite material logistics. Offsite construction logistics is part of supply chain management, in which various firms work collaboratively forming a network of inter-related processes to move material, services, funds and information in an effective way that reduce total costs, decrease total lead time, and improve total profits, keeping customer's value above all goals (F. R. Hamzeh, Tommelein, Ballard, & Kaminsky, 2007). Whereas site material management may be defined as the practice of allocating spaces for resource delivery, storage, and handling in order to reduce site congestion and excess material movement, so that inefficiencies are minimized (Randolph, Riley, & Messner, 2005). Site material management affects then labors' productivity on site, which is an important factor that substantially affect time and cost of construction projects.

Balancing supply with demand is an important aspect in supply chain management (Cachon & Terwiesch, 2006), including onsite construction logistics. Material shortage or excess material can both cause disruption to construction activities. That is why site material management is necessary on all construction sites. Yet, small and medium size projects tend to give less attention to site material management, that is because contractors on such projects use milestone schedules with little detailed construction planning of activities, which does not focus on material procurement and management. Material management convers five main categories: material specifications, procurement to supplier, delivery to site and storage, administrative and financial process of payment, and finally utilizing material and waste collection (Donyavi & Flanagan, 2009).

This research is concerned with material logistics on congested sites, then literature will be narrowed to site material management and onsite logistics.

Site material management may be defined as controlling material delivery and storage, handling resources and allocating spaces in order to support labor force and reduce inefficiencies (Randolph et al., 2005).

Site material management principles mainly aim to reduce transportation costs and travel distances on large uncongested construction sites. Whereas on congested sites, site layout is specifically important and principles targeting labors' productivity and safety are of primary importance. This is why the link between site layout and material management is important on congested sites (Randolph et al., 2005). Site layout include six main function areas: site entrances, laydown areas, staging areas, assembly areas, installation areas or workplace, and waste areas (Tommelein, 1994).

Moreover, Randolph et al. (2005) identified some main principles of site material management. These principles include minimizing the material storage inside the building, preassembling components into larger components or preassemblies, integrating schedule with the storage plan to manage interior spaces usage with work, performing ancillary tasks (unpacking, cutting, etc.) away from the workplace when practical, maintaining good housekeeping, and balancing between delivery and installation work on site.

Balancing between delivery and installation is especially important on congested sites, such as urban building construction projects, where there is no wide external space that can handle the material storage and temporary facilities (Said & El-Rayes, 2013). This limited availability of space may be addressed by just-in-time delivery, which requires proper coordination with suppliers (Horman & Thomas, 2005).

Then on congested construction sites, material storage layout should be well planned to comply with safety and operational constraints while minimizing resource travel cost and handling time (Said & El-Rayes, 2013). Moreover, the construction activities to be performed inside the building should be scheduled in a way to maximize space for material storage without affecting the schedule criticality (Randolph et al., 2005). And in case interior spaces are not efficiently utilized, exterior spaces may be more crowded which reduce productivity and safety, and material that may have been ordered in bulks (which reduce unit and transport cost) are to be ordered with less amounts (Said & El-Rayes, 2013).

Some studies discussed site material management principles and effective site layout on typical construction sites to reduce logistics costs and time delays (Akinci, Fischer, & Kunz, 2002; Harmanani, Zouein, & Hajar, ; Jang, Lee, & Choi, 2007; Lee, Choi, Cho, Park, & Kim, 2014; Said & El-Rayes, 2013). Only few researches considered effective handling of materials on site which reduces waste and increases labor productivity, yet the way this issue is addressed was though material storage techniques and not through on-site material logistics (be it push or just-in-time) from storage places to workplaces.

Focusing more on the effect of onsite material logistics on productivity, it was mentioned in many papers that insufficient material distribution methods, extensive multiple handling of material, improper material sorting (mismatching materials to locations), material shortage, and trash obstructing access and material movement are factors that reduce labor productivity on construction sites (Tommelein, 1998; Thomas, Sanvido, & Sanders, 1989; Randolph et al., 2005; Abdul Kadir, Lee, Jaafar, Sapuan, & Ali, 2005; Singh, 2010; El-Gohary & Aziz, 2013).

Moreover, Seppanen and Peltokorpi (2016) studied the effect of on-site logistics on labor productivity, through reviewing what factors (and factor's interconnections) were linked to productivity. The authors found out that the direct impact of storage locations on labor productivity due to skilled labor moving material was not clearly covered in the literature (Seppanen & Peltokorpi, 2016).

B. Production Planning and Control

After presenting production planning and control in the introduction, this section focuses more how push and pull techniques are implemented in production control.

Traditional planning and controlling approaches are mainly applied push-driven techniques. Construction projects are planned by forming the activities along with their relations, resources and durations, and then schedules calculate the start and finish dates based on the critical path method (CPM) (Kelley Jr and Walker 1959). Project control then tries to stick to the planned schedule during execution assuming that all resources needed to start an activity will be available once an activity start date is reached. Thus once the activity is released after its predecessor is done, it waits passively until all the required constraints are removed. Constraints include the availability of material, information, labor, equipment and space. In case of the availability of some ingredients and the lack of others, those available ones have to wait in a queue, or the activity may start with partial requirements, also called making-do (Koskela 2004), with high probability of losing expected productivity (Tommelein 1998b; Thomas, Sanvido and Sanders 1989b; Howell et al. 1993).

Although some schedules account for uncertainties that could arise during execution such as uncertainty in duration and dependency logic, dealing with these uncertainties during real time execution should not be through trying to adhere to the planned schedule. This is because the actual network conditions and resource availability may differ from those assumed during planning (Tommelein 1998b). Thus the traditional push approach used in schedules, and the way of controlling production during execution with no appropriate rescheduling affect project performance negatively.

An alternative approach for production planning and control is the pull system. This system allows the end user to pull value from the producer (Koskela 2004). It is a demand driven system that only allows information and material to pass to a system only if the system is capable of handling them (Ballard 2000). Unlike a push system that forces the implementation of the schedule, pull systems prioritize the release of work based on the actual state of the system (Hopp and Spearman 1996).

1. Last Planner System (LPS)

Last Planner System (LPS) is considered a pull controlling system, as it ensures that all constraints are removed before allowing an activity to start (Ballard and Howell 1998). Location Based Management System (LBMS) also applies lean theories through aiming at reducing waste, decreasing variability, and increasing productivity. It can be applied in a pull fashion by accepting additional crews on site only when locations are available (Seppänen 2009). Moreover, the combination of both systems (LPS and LBMS) can lead to better project performance (Seppänen et al. 2010)

Last Planner System (LPS) breaks down production planning and control into four main planning processes: Master scheduling, phase scheduling, lookahead planning, and weekly work planning. Through this system, project activities move from general planning (phases) into more specific processes, then into detailed operations (F. Hamzeh et al., 2012).

Traditionally, all resources are assumed to be available once an activity is to start, and then what happens is that those activities wait all their resources and prerequisites to be available; this is known as a push-driven approach (Tommelein & Ballard, 1997).

Whereas in LPS, specifically in lookahead planning, constraints are identified and removed through activity screening and pulling. In activity screening, activities are categorized into ready and constrained activities, where constraints can be prerequisite activities, required information, material, labor, space, etc. Then pulling is applied to make constrained activities ready through removing these constraints in accordance to actual site demand (F. Hamzeh et al., 2012). This method could be broken down into clear steps to have a complete weekly lookahead process, these steps include:

- Identifying tasks and locations in the look-ahead window.
- Breaking down tasks and locations to operations.
- Identifying, assigning and removing constraints.
- Reviewing actual production to identify ongoing production problems.
- Reviewing forecasts and alarms to identify future production problems.
- Finding the root causes for problems.

- Re-Planning to address current and upcoming problems.
- Releasing constraint-free operations, tasks and locations to workable backlog.
- Preparing for upcoming operations.

These steps are not meant to be applied in the sequence provided, where some iterations may take place on the process (Seppanen, Modrich, & Ballard, 2015).

2. Location Based Management System (LBMS)

Location based management system may be defined as an iterative design method for planning and controlling construction work in order to achieve a continuous flow of work (Frandson, Seppanen, & Tommelein, 2015). This management system requires various inputs including Location Breakdown Structure (LBS), tasks to be completed along with their quantities, locations, labor consumption rate, work hours for each task, etc. (Kenley & Seppänen, 2010).

LBMS considers clearly defined physical location, and define tasks as activities to be completed by one trade in a location before moving to other locations (Frandson et al., 2015). Moreover, LBMS tends to create a velocity diagram or a Line of Balance "LOB" showing task completion in each location versus time. These lines may have a gentle or a steep slope depending on their corresponding consumption rate. This allows visualization of "bottleneck" tasks, which are those with gentle slopes, and allow for optimization through adjusting the slope through changing the number of crews, or scope, or through changing the location sequence, or through splitting tasks, or other approaches (Kenley & Seppänen, 2010).

CHAPTER 3

RESEARCH MOTIVATION AND OBJECTIVES

A. Problem Statement and Motivation

Construction Logistics and production control systems are associated with problems that can affect project's performance and disrupt workflow, which may lead to negative impacts on the project's cost, duration, and quality. Thus, research has focused on different systems of Logistics and control for reducing induced losses and delays on construction projects. Besides, it was noticed that research discussed different production planning and control systems that apply pull techniques, such as LBMS and LPS. Moreover, traditional push method or CPM was contrasted to pull techniques from scheduling and control perspectives, considering tasks and project durations. However, zooming into the level of crews and locations within the project, the effects of pull vs push production control approaches on crew productivity, crew logistics between locations within a construction site, and interactions between crews in the same location are still not clear enough. These presented gaps are of high importance as crews' behavior and the level of interaction between them on site can change the overall project performance, though affecting productivity, project duration, labor cost and many other essential metrics. All of this brings the need to study the issues presented and fill these gaps.

B. Research Objectives

The research gaps presented in the previous section are addressed through the following objectives:

Objective 1: Understand the role of production planning and control on congested sites, and study methods of implementing push and pull planning at the level of locations:

Production planning and control are complex practices that should be well considered on small, medium, and large-scale projects. Through this research, push (traditionally applied in CPM method) and pull (addressed in LPS and LBMS) techniques are studied and compared. Besides, new techniques that are based on pull concepts are suggested and analyzed. These techniques are mainly used for resource allocation to tasks, crew logistics between project locations, and handling of late tasks.

Objective 2: Test and analyze the effect of push and pull techniques on crews' and project's performance metrics through a location-based approach:

In order to analyze and compare production control techniques, this research will study and model the effect of pull and push techniques on various crew performance metrics including labor productivity, crew turnover rates (number of times crews change their location), crew allocation to areas, crew interactions while working in the same area, idle time of crew, distances traveled by crews, and utilization of manpower. Results from data analysis of these metrics give a representative vision on the strengths and weaknesses of the techniques used, which would be summarized in generalized recommendations that could be implemented to resolve various issues on construction projects.

C. Research Questions

The main research questions may be stated as follows:

Question 1**:** From a location-based perspective, how can push and pull techniques be used for project control?

Question 2: From a location-based perspective**,** what is the impact of push and pull planning techniques on labor productivity and crew logistics?

CHAPTER 4

RESEARCH METHODOLOGY AND METHODS

In order to address the objectives stated above, the following methodology, shown in figure 1, was followed: 1)Literature review, 2)Problem identification and research objectives, 3)Development of a conceptual models, 4)Specification model 5)Computational model 6)Model validation and verification, 7) Model experiments 8)Result analysis and conclusions.

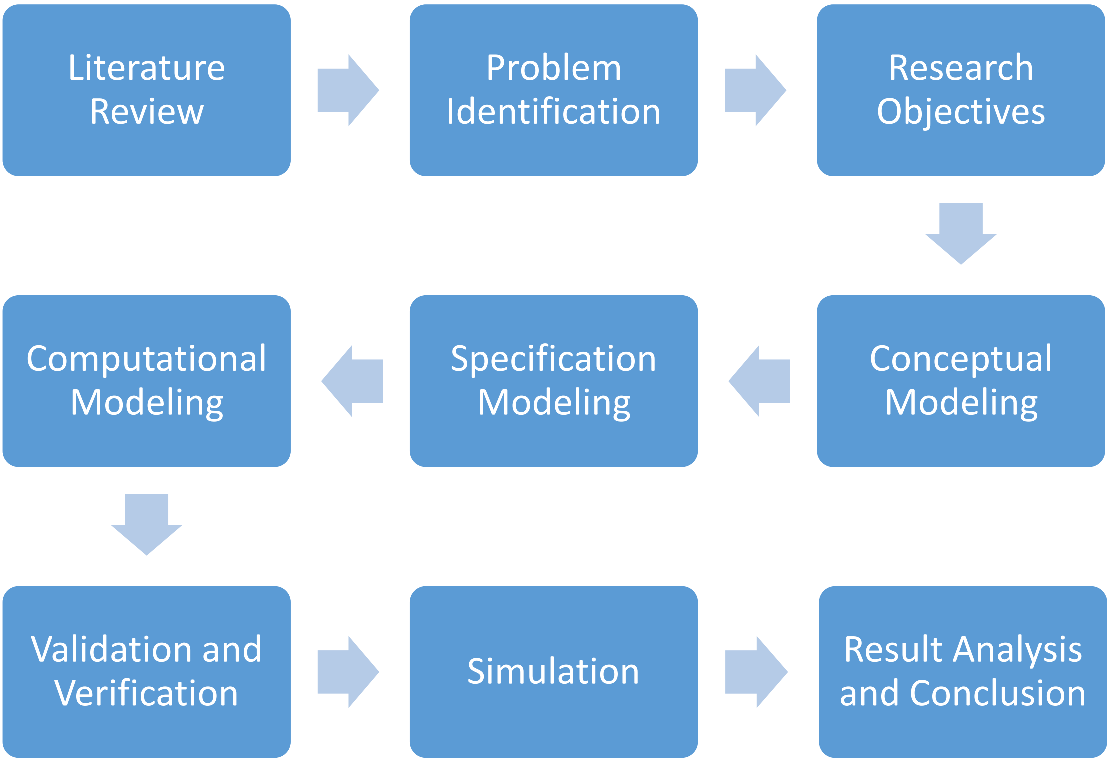

Figure 1 Methodology diagram

A. Knowledge acquisition and background research:

A detailed literature review was conducted on construction logistics and production control. In addition, labor productivity on construction sites was studied in terms of definition and factors affecting it. Some studies discussed the effects of different factors, such as congestion, on productivity. This research further analyzed how different production control affect productivity. Results were founded on the modeling of a real construction site by simulating push versus pull production control techniques while monitoring various parameters that help in assessing the results.

B. Problem Identification and Research Objectives

After conducting a literature review, some gaps were identified. These gaps are presented in the Problem Statement section, and addressed through the objectives mentioned earlier. These objectives were addressed through modeling and simulation in order to visualize and test the effects of push and pull techniques on different project performance metrics.

C. Modeling and Simulation

1. Conceptual Model

The aim of the model is to test the effect of push versus pull techniques in production control on different project performance metrics including labor productivity and project duration. In order to achieve this, and since modeling pull and push scenarios change many parameters during simulation time such as congestion, productivity, and other main factors, agent based modeling is chosen to mimic this behavior. The conceptual model is explained in details in the following chapter.

2. Specification Model

A specification model explains how exactly the model receives the input; it may include equations, pseudocodes, functions, etc. This model specifies the agents used, parameters, variables, and interactions that are govern agents' behavior. The main agents used are Crew and Activities. Agents' attributes and the functions that govern relations between them are discussed in details in the following chapter.

3. Computational Modeling

AnyLogic 7.3.1 was used as the modeling platform. The agents described previously interact in an environment that resembles a construction site. Moreover, data including activity types and quantity of work to be executed was used from a real construction site. Besides, multiple scenarios of push and pull were generated and results were collected and analyzed.

4. Validation and Verification

In order to validate the model and to know if "we built the right model", different validation tests were conducted that ensure a proper operational behavior and acceptable variability. To verify the model, extensive testing was performed to assure that "we built the model right". The model logic, coding, and interaction functions were tested. Moreover, a software and coding specialist was consulted for advanced coding checkups. Validation and verification of the model are discussed in the chapter 6.

5. Simulation Runs and Result Analysis

After developing the conceptual and computational models, multiple simulation runs of push and pull scenarios were generated. During simulation, several metrics were measured and stored in parameters and datasets, and after each run, results were extracted to excel sheets were data was further processed and analyzed. Then after having enough simulation runs, the collected data were used to test several hypothesis concerning production control techniques and their effects on crews and project performance. Finally, results were analyzed reaching comprehensive conclusions and recommendations.

CHAPTER 5

AGENT-BASED MODEL

A. Conceptual Framework

A conceptual framework is developed to study the effects of push versus pull techniques in production control on different project performance metrics.

In order to test how different techniques affect crew performance, there was a need to model how crews work on a construction site, how they interact with each other, and how their productivity is being affected. Thus, the model is mainly composed of crews of various trades working in an environment representing a construction site. Activities they perform are also modeled, each having various parameters that include the space required by crews, locations, predecessors and successors, resources needed for each activity, etc. The considered activities include drywall, casework, several MEP works, paint, besides other finishing activities. The model simulates scenarios where activities happen based on a pre-set schedule (push system), and other scenarios where activities are executed based on the status of the system and the actual need downstream (pull system).

Push technique at the level of locations means forcing the implementation of the schedule through assigning crews to activities as per the plan, paying less attention to their anticipated productivity. This technique is demonstrated in Figure 2 that shows crew logistics between areas following a push system.

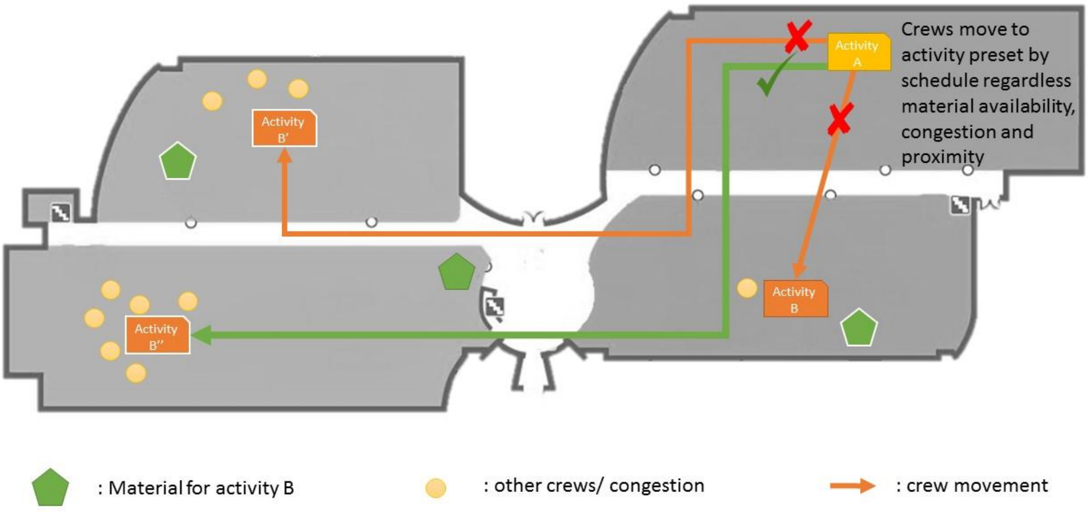

Figure 2 Crew logistics between areas following a push system

As shown in Figure X, when the crew finishes task "A" in a location and needs to perform the same task in another location, based on a push system, the crew typically moves to the task/location that is pre-set by the schedule, which may not account for material availability, material hauling distance, congestion caused by other crews in the location, proximity between locations, and other factors (Ghanem et al., 2018).

In this specific example, it happens that the crew moves to a location that:

- Is relatively more congested than other available areas.
- Requires material hauling over a larger distance compared to that in other areas.
- Is relatively farther than other available locations.

Now consider a pull technique that is applied for the same scenario. This is demonstrated in Figure 3, whereby all of these three alternatives are assessed taking into consideration the schedule, material availability, and anticipated production rate or congestion in the available locations . The main purpose of evaluating these alternatives is to choose the location that allows for higher labor productivity through pulling from milestones (schedule) and from the state of the system (actual conditions of congestion, material availability, etc.).

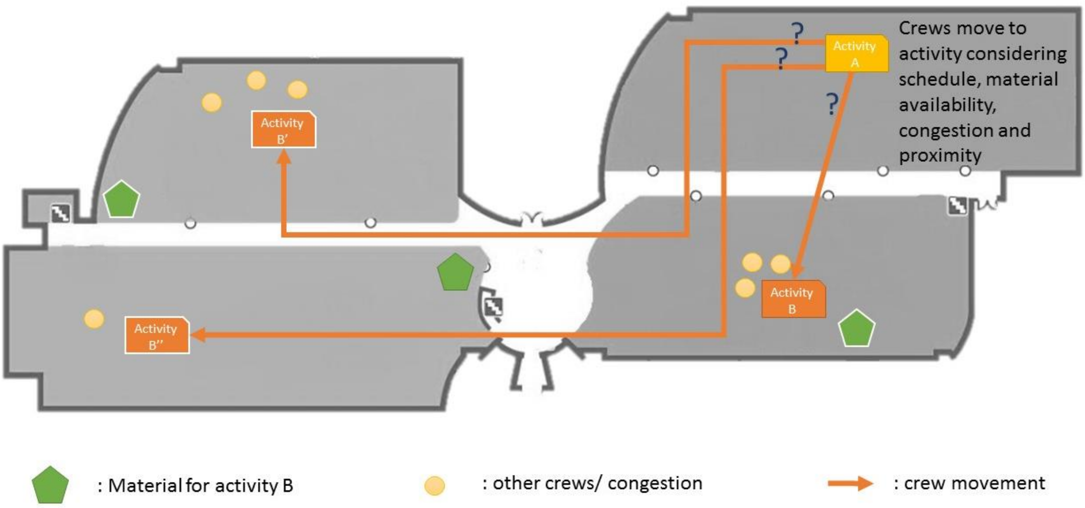

Figure 3 Crew logistics between areas following a pull system

Another implementation of push technique is when subcontractors work out-of-sequence or in parallel locations leaving unfinished work, without active management from the general contractor. Moreover, subcontractors tend to handle late activities through allocating more crews to a late activity in order to increase its production rate (Seppänen 2012). Push techniques can thus increase production rates when tasks are delayed but they can cause overmanning and thus may lead to a loss in productivity (Thomas 1992; Singh 2003). This shows the need to use pull techniques in production control that are expected to help in increasing labor productivity and production rate at the same time.

Modeling these techniques depends on many dynamic conditions including the way crews interact with each other. These complex behavioral interactions along with their effects on crews and project performance are hard to be expressed through regular analytical mathematics. This is why agent based modeling is used. It allows revealing non-linearity, emergence, and dynamic change through a simplified and understandable virtual model.

B. Agent-based Simulation Model

After developing a conceptual framework, the working environment in addition to the dynamic interactions between crews and activities are modeled through agent-based modeling. The main environment considered in this study is the construction site, where crews of different trades interact and work together on different activities. The main agents used are Crew, Activities and Locations. To better understand this model, Figure 4 shows the environment and the agents along with their attributes.

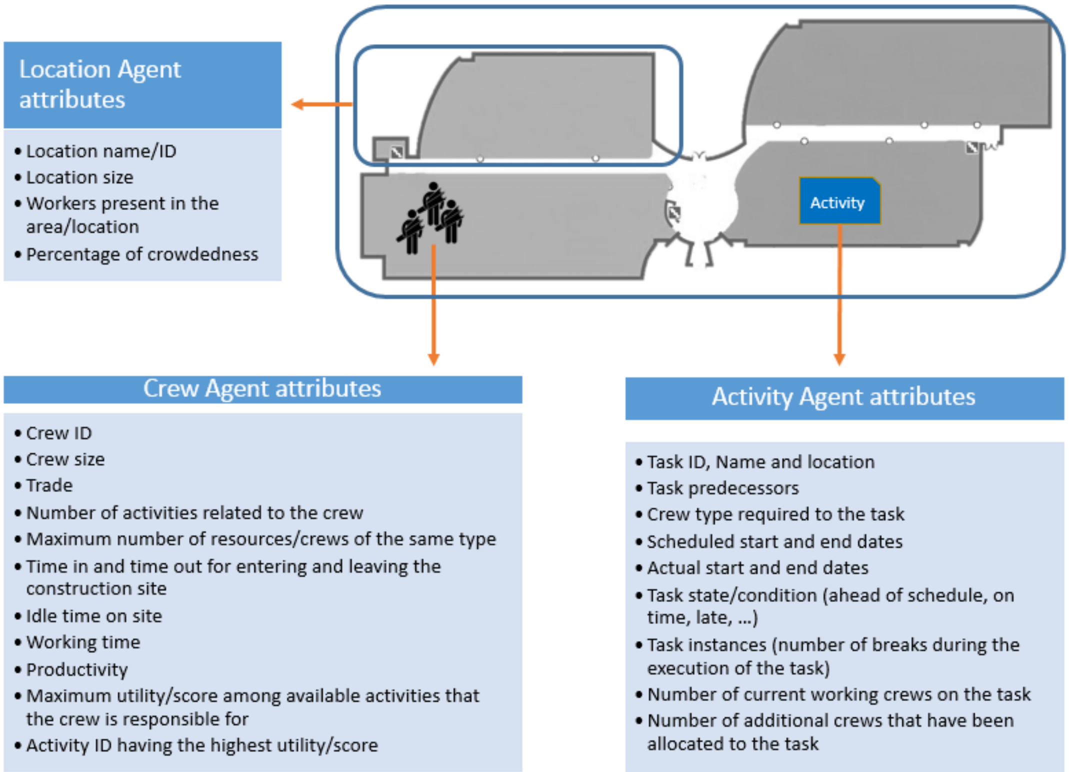

Figure 4 Main environment and the agents along with their attributes

As shown in Figure 4 above, every agent has the attributes required to keep track of its behavior and its relation with other agents. Note that in order to initialize the model in a logical manner, data used to initialize the agents attributes and parameters is used from a real construction project, which is Camino Medical Office Building located in California, USA. This is discussed further in the Validation section of this Chapter.

The following sub-sections describe each agent in addition to the functions and communication methods that govern their interactions.

1. Crews Agents

"Crews" Agents represent all crews of different trades. These agents form an essential part of the model; their behavior and the level of interaction between them on site can change the many project's performance metrics. Every type of crews has a set of attributes that are defined in Table 1 below.

Table 1 Crew types and their attributes

Crew Nb	Trade	Number of Tasks to be executed	Crew Size (members/ crew)	Max. number of crews
1	Casework	15	2	12
2	Ceiling Tile	27	2	12
3	Doors, Frames and Hardware	19	2	4
4	Drywall	70	2	20
5	Electrical	95	1	12
6	Fire Sprinkler	12	1	3
7	Flooring	15	2	12
8	Mechanical	65	1	16
9	Painting	16	1	8
10	Plumbing	25	1	8
11	Specialties	19	1	1

As shown in the Table 1 above, there are 11 different crew types, each specialized in a single trade, and responsible for certain number of tasks on the project. Crews are mainly composed of either 1 or 2 individuals, and there are maximum numbers of crews available for each trade.

These crews are represented in Anylogic by a “Crew” population agent, each having the attributes shown in Figure 5.

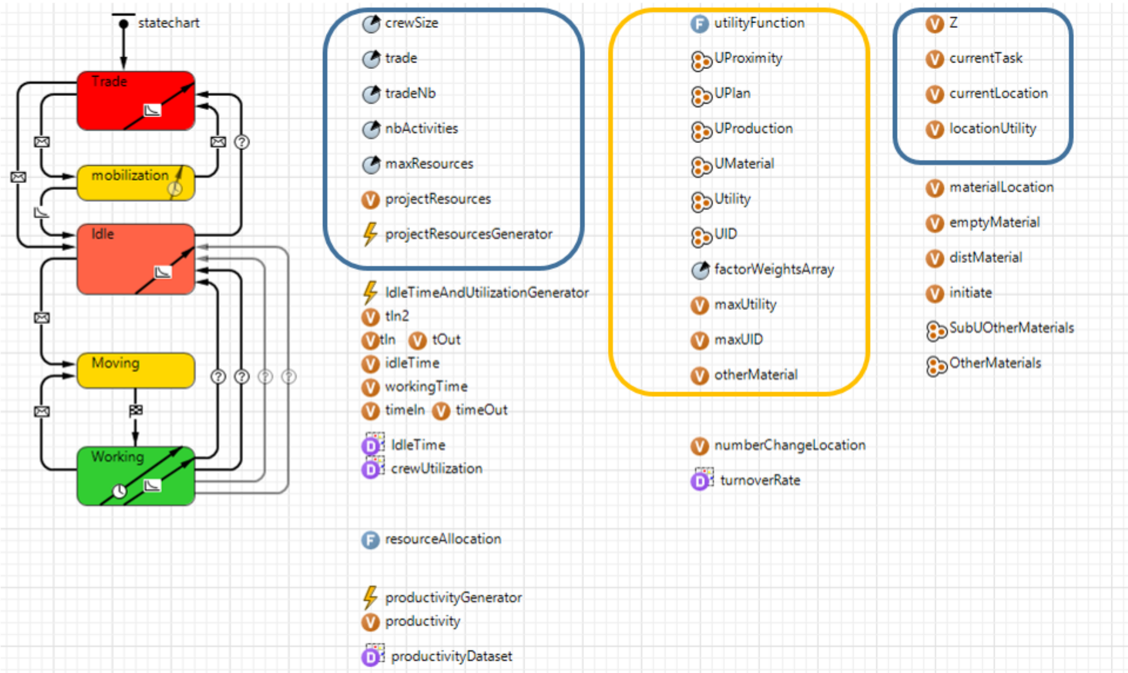

Figure 5 "Crew" population agent screenshot from AnyLogic

The parameters and variables indicated in blue zones in the Figure above are attributes that characterize each crew. Note that parameters have fixed values throughout the model simulation time, whereas variables have values that can change with time. The parameters are defined for each crew through model initialization, such as crew size, number of activities to be executed by each type of crews, the maximum allowable resources (crews) that can be moved to the site if needed, etc. Variables indicated by blue zones summarize information for each crew that change during simulation; this includes the current task that the crew is executing, the current location, etc. The orange zone indicates the Utility Function along with its collections and variables. This function is explained later in details. Some of the other events and variables are used to calculate the idle time and working time for each crew, which are calculated at the end of each working day showing how many hours of that day a crew spends in the idle state or working state. Besides, the number of locations visited by each crew is recorded.

Concerning productivity, initial values are used for different types of crews. A crew may have different productivities (units/hr) depending on the task it is executing. Besides, productivity is affected by congestion, which is in this case caused by overmanning. Thus, a reduction factor is multiplied by the productivity of each crew depending on the level of congestion/overmanning in the area the crew is working in. This factor is calculated using the graph adapted from the US Army Corps of Engineers (1979) shown in Figure 6.

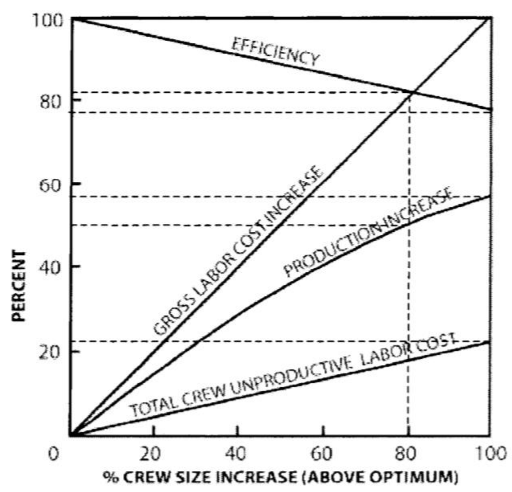

Figure 6 Composite effects of overmanning (US Army Corps of Engineers (1979))

The graph shows a linear relation between the percentage increase of crew size beyond optimum and the efficiency (productivity). This linear relation is transformed to the following equation that is used in the model:

$$F = -0.23x + 100$$

Equation 1 Productivity reduction factor

Where:

- F: the reduction factor to be multiplied by the initial productivity of each crewmember.
- x: the percentage increase in the crew size above the optimum number of crews.

Note that the graph presented in in Figure 6 shows the percent increase in crew size up to 100% only. However, for this model, the same relation between the crew size increase and productivity is assumed to continue in the same behavior after 100% increase in crew size. Besides, a lower limit of the reduction factor "F" is used to avoid having very low (unrealistic) or negative values of productivity. The boundary used is 0.4 (40% reduction in the initial productivity).

The optimum number of crews is assumed to be 3 crews for all activities before partitioning, and 2 crews for activities after it, considering that the area available for crews to work in would be less. Then "x" will be:

$$x = \frac{number\ of\ working\ crews - a}{a} \times 100$$

Equation 2 Percentage increase in the crew size above the optimum number of crews

Where "a" equals:

- 3: if the task executed by the crew is before partitioning
- 2: if the task executed by the crew is after partitioning

Moving to the behavior of each crew, the state chart shown in the Figure 5 indicates the behavioral states each crew passes through, along with the conditions that determine the transitions between these states. These states are described in the Table 2.

Table 2 Behavioral states for each crew agent

State	Description	Transition Process
Trade	This state indicates that a crew is out of the construction site. A crew generates "resource allocation" function while it is in this state.	Each crew enters the state chart to this state
Mobilization	This state provides a mobilization delay when a crew is moving to the construction site	When a crew receives a message "mobilize", which is sent from resource allocation function when a crew is required to execute a task on the construction site.
Idle	This state represents the case when crews are idle on the construction site. When a crew is in this state, it generates the "utility function" and looks for activities to be executed.	After a crew finishes the mobilization delay, or when a crew finishes the activity that it was working on
Moving	The state of crew movement from/to a location to perform a task.	When a crew receives a message "move" from the utility function
Working	This state indicates that a crew is assigned to a task and thus working on it	A crew reaches this state automatically after "Moving" state. It leaves it back to "Idle" state once the activity is finished, or once the utility of this activity becomes zero.

The states and transitions described in Table 2 represent the different phases a crew passes through on an actual construction project. The conditions and functions mentioned in the states description define the interactions between these agents, and the way they are assigned to tasks. One of the main functions used is the "Utility Function", which is described in the following sub-section.

a. <u>Utility Function</u>

This function is the main driver that determines what is the next task to be performed by each crew, and where it is located. This function accounts for push and pull techniques (two scenarios), and it takes into consideration proximity between locations, schedule, and anticipated production rate by the crew.

Each of the three factors is translated into a numerical value (score out of 100), each with a certain weight, and then Equation 1 is used to calculate a global score, and the task having the highest score will be the next task to be executed.

$$utility = \frac{U_{Proximity} \times W_{Proximity} + U_{Plan} \times W_{Plan} + U_{Production} \times W_{Production}}{W_{Proximity} + W_{Plan} + W_{Production}}$$

Equation 3 Utility Equation

Where:

- $U_{Proximity}$: accounts for the distance between the current location of the crew and the next location. The preference is to move close to current location.
- U_{Plan}: accounts for the plan/schedule logic. It gives higher scores to activities that should start according the schedule, and lower scores to activities that follow.
- $U_{Production}$: Anticipated production rate, it accounts for congestion in places that the crew will move to. Places with relatively less crowd score higher than other more congested locations.
- $W_{proximity}$, W_{Plan}, and $W_{Production}$: weights assigned to each factor. These weights change between push and pull scenarios.
  - For push scenario:
    - $W_{proximity}$=0.1
    - W_{Plan}=0.8
    - $W_{Production}$=0.1
  - For pull scenario:
    - $W_{proximity}$=0.3

- W_{Plan}=0.35
- $W_{Production}$=0.35

In push scenario, the dominant factor is U_{Plan}, to represent the fact that production is being controlled mainly by the schedule, paying less attention to the other two factors. Whereas in pull scenario, the three factors are considered as follows: U_{Plan} and $U_{Production}$ contribute to 70% of the total utility score (both having same weight: 0.35) whereas $U_{Proximity}$ contributes to the remaining 30%. The reason behind this is that in a pull scenario, anticipated productivity and the schedule are almost of equal importance when it comes to choosing the task to execute next. Proximity is also important, however it is assumed to have less impact on the decision; even though moving to a closer location within the project is better for a crew, the crew spends much less time moving between locations than working in a location, hence they care relatively less of this factor compared to the other 2 factors.

The factors described above are further explained in the following

1. $U_{Proximity}$:

The scoring system used for $U_{Proximity}$ calculations favours horizontal movements rather than vertical ones, assuming that it is easier to change location within the same floor than changing the floor.

As shown in Figure 7, there are five locations per floor.

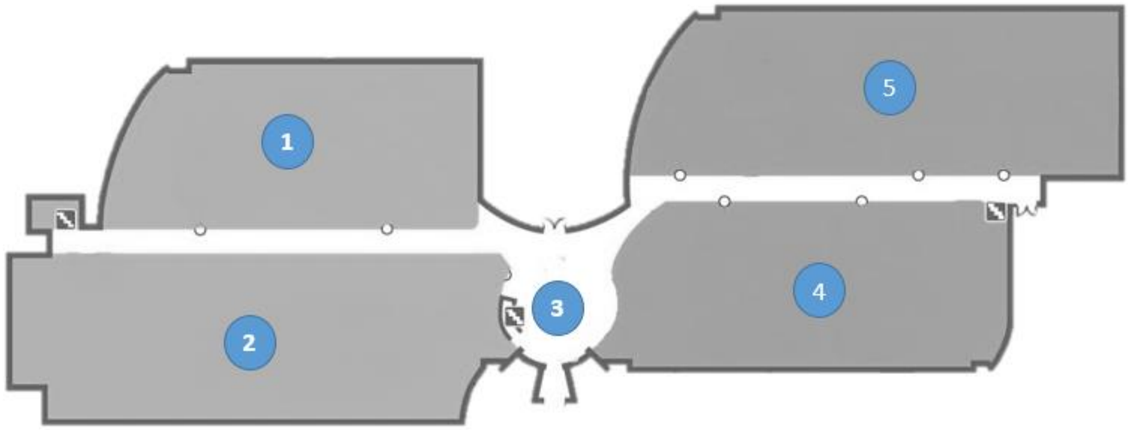

Figure 7 Location IDs per floor

If the finished task and the upcoming one are in the same floor, $U_{Proxiity}$ will have a value between 80 and 100 according to the following conditions:

$U_{Proximity}$ equals:

- 100, if tasks are in the same location
- 95, if tasks are in adjacent locations (ex: locations 3 & 4)
- 90 if tasks are in 2 close non-adjacent locations (ex: locations 2 and 4)
- 85 if tasks are in 2 far non-adjacent locations (ex: locations 1 and 4)
- 80 if activities are in farthest locations (locations 1 and 5)

If tasks are in different floors, $U_{Proximity}$ takes one if the following values:

$U_{Proximity}$ equals:

- 60, if tasks are in successive floors (ex: floors 1 and 2)
- 40, if tasks are in 2 close non-successive floors (ex: floors 1and 3)
- 20, if tasks are in the farthest floors (floors 1 and roof)

2. U_{Plan}:

This factor gives scores out of 100 to all tasks that are not executed yet. Scores are given according to Finish-to-Start relationship between tasks in the same floor, so the first task to be executed in each floor is given a score of 100, the last task scores 0, and the remaining tasks in between receive equally proportioned scores between 0 and 100. For example, assume that there are 5 remaining tasks (A, B, C, D, and E successively) to be executed in a certain location, scores will be as follows:

- A: U_{Plan}=100
- B: U_{Plan}=75
- C: U_{Plan}=50
- D: U_{Plan}=25
- E: U_{Plan}=0

Moreover, incase tasks at different floors are unconstrained at the same time, the scoring system prioritizes tasks that started earlier. For example, the first task at the lower floor scores 100 and that located at the floor above scores 90, then scores of the remaining tasks are updated accordingly.

3. $U_{Production}$:

This factor is a score out of 100. It is determined based on the percent of congestion in each location. A task taking place in an empty location where no other crews are available takes a score 100. The equation used to calculate $U_{Production}$ is the following:

$$U_{production} = 100 - 100 \times \%congestion = 100 - 100(\frac{N \times a}{A})$$

Equation 4 $U_{Production}$ factor calculation

Where:

- N: number of crewmembers working in the considered location
- a: the area required by each crewmember
- A: area of the considered location.

This relation between congestion and the anticipated production rate is assumed to be linear to avoid a complex model with minimal added value. Besides, since the area of each location is very large compared to the typical area required by a crewmember (a location's area is around $1400m^2$ on average, which is very large compared to the area needed by a crewmember), it is assumed that each crewmember needs $70m^2$ to work productively for tasks before partitioning and $100m^2$ for tasks after partitioning. Note that these assumptions are only to be used by crews to anticipate their productivities, and not to calculate their actual productivities while working on a task.

Another function that affects crews' behavior is Resource Allocation function. This function allocates crews to activities based in several conditions. It sends crews from "Trade" state to "Mobilization" state, or directly to the construction site, arriving at "Idle" state, whereby the utility function explained previously runs in this state and the appropriate task is determined.

b. Resource allocation function:

This function runs only if the crew is at the "Trade" state. In both scenarios (push and pull), once a task is unconstrained, a random number between 1 and 3 crews are sent directly to the project. In this case, there is no mobilization delay, since it is assumed that the subcontractor is notified before the task becomes unconstrained, and thus the subcontractor mobilizes the crew before. The number crews may not be suitable for the specific task, if it was greater than what is needed, production rate increases accordingly and task's condition will become "early", then crew number is adjusted to fit the desired production rate. The same concept applies if the number was less than what is actually required.

Besides, this function allocates crews for tasks that become late during execution. The way crews are sent to the construction site differs between push and pull.

In the "push" scenario:

Once a crew is at Trade state, it keeps checking for activities' conditions:

- If a task related to the crew's trade is late
- If number of crews working on this late task < 75% of the maximum available resources

Then "x" crews are mobilized to the project, where "x" is the number of additional crews required to have number of working crews equals 75% of the maximum resources.

- If a task's condition is "end date exceeded"
- If number of crews working on this late activity < maximum resources – 1

Then "x" crews are mobilized to the project, where "x" is the number of additional crews required to have number of working crews the task considered equals maximum resources minus one crew.

It could be noticed that in a push scenario, and as described in the conceptual model, late activities are usually addressed through allocating more crews to the task to increase the production rate.

Note that defining each task's condition (early, late and end date exceeded) is explained in details in "Activities" agent sub-section.

In the "pull" scenario:

- If an activity is late
- If number of crews working on this late activity < optimum number of working crews

Then mobilize "x" crews to the project, where "x" is the number of additional crews required to have number of working crews equals optimum number of crews.

Note that considering the optimum number of crews, literature shows theoretical methods for determining the optimum crew number that minimizes the cost (ex: Gates and Scarpa (1978)). However, regarding the optimum number after which productivity starts to decrease, it is usually determined by the subcontractor who has the know-how to determine the optimum number of crews for a job (Lee 2007, p: 233). In this model, the optimum number used is based on the resource data taken from the actual construction site, (Al Camino Medical Office Building in California, USA) assuming that this number of crews used to work on tasks during normal conditions favours high productivity.

So to conclude on "crew" agents, it could be said that the way crews and their behavior were modeled in the push scenario similar to their actual behavior on traditional construction projects. On the other hand, alternative methods that determine crews' behaviors and interactions were represented in the pull technique. Another important agent used in this model is "Activity" agent; it is described in the following sub-section.

2. *Activity Agents*

This agent population includes all the activities and tasks to be executed on the construction site. The activities used in this model are summarized in the Table 3 below:

Table 3 Activities used in the model

ACTIVITY NUMBER	ACTIVITY	CREW TRADE REQUIRED
1	Frame priority full height walls etc.	Drywall
2	Sprinkler Rough	Fire Sprinkler
3	Medium pressure duct	Mechanical
4	Mechanical Rough	Mechanical
5	VAV and Low Pressure Ducts	Mechanical
6	Domestic Water	Plumbing
7	Rain Water Leaders, Waste and Vent	Plumbing
8	Branch conduit	Electrical
9	Feeder conduit	Electrical
10	Wall, Hard Ceiling, and Soffit Framing	Drywall
11	Wall, Hard Ceiling, and soffit MEP Roughing	Mechanical
12	MED GAS	Plumbing
13	Cable Tray	Electrical
14	Tele/data, Nurse Call, Security, AV, and Fire Alarm	Electrical
15	Drywall	Drywall
16	Tape and Finish	Drywall
17	Paint	Painting
18	T-Bar	Ceiling Tile
19	Light Fixtures, Diffusers, Ceiling Mounted Trim	Electrical
20	Ceiling tile	Ceiling Tile
21	Casework, Millwork	Casework
22	MEP Trim	Mechanical
23	Floor coverings	Flooring
24	Specialties and accessories	Specialties
25	Doors & Hardware	Doors, Frames and Hardware

These activities will be repeated in 20 different locations at the project (some activities are not present in all locations). Further details are provided for each task at each location. Sample data for activities on Northwest location - Floor 1 are presented in Table 4.

Table 4 Tasks in location SE1

LOCATION	ACTIVITY	TASK ID	CREW TRADE REQUIRED (TYPE AND ID)		PREDECESSOR	UNIT	QUANTITY	LOCATION ID	CONSUMPTION RATE (HR./UNIT)
SE1	Frame priority full height walls etc.	1	Drywall	4		(lf)	1000	1	0.250
SE1	Sprinkler Rough	2	Fire Sprinkler	6	1	(lf)	2120	1	0.070
SE1	Medium pressure duct	3	Mechanical	9	2	(lf)	500	1	0.100
SE1	Mechanical Rough	4	Mechanical	9	3	(lf)	1500	1	0.100
SE1	VAV and Low Pressure Ducts	5	Mechanical	9	4	(lf)	4000	1	0.100
SE1	Domestic Water	6	Plumbing	11	5	(lf)	2000	1	0.070
SE1	Rain Water Leaders, Waste and Vent	7	Plumbing	11	6	(lf)	2500	1	0.040
SE1	Branch conduit	8	Electrical	5	7	(lf)	3000	1	0.064
SE1	Feeder conduit	9	Electrical	5	8	(lf)	2000	1	0.100
SE1	Wall, Hard Ceiling, and Soffit Framing	10	Drywall	4	9	sq.ft.	1900	1	0.040
SE1	Wall, Hard Ceiling, and soffit MEP Roughins	11	Mechanical	9	10	No.	25	1	0.300
SE1	Cable Tray	12	Electrical	5	11	(lf)	250	1	0.053
SE1	Tele/data, Nurse Call, Security, AV, and Fire Alarm	13	Electrical	5	12	(lf)	3000	1	0.008
SE1	Drywall	14	Drywall	4	13	sq.ft.	36000	1	0.013
SE1	Tape and Finish	15	Drywall	4	14	sq.ft.	36000	1	0.007
SE1	Paint	16	Painting	10	15	sq.ft.	36000	1	0.008
SE1	T-Bar	17	Ceiling Tile	2	16	sq.ft.	30000	1	0.014
SE1	Light Fixtures, Diffusers, Ceiling Mounted Trim	18	Electrical	5	17	No.	464	1	0.500
SE1	Ceiling tile	19	Ceiling Tile	2	18	sq.ft.	30000	1	0.007
SE1	Casework, Millwork	20	Casework	1	19	lf	2000	1	0.200
SE1	MEP Trim	21	Mechanical	9	20	No.	75	1	0.500
SE1	Floor coverings	22	Flooring	8	21	sq.ft.	30000	1	0.018
SE1	Specialties and accessories	23	Specialties	12	22	No.	75	1	0.200
SE1	Doors & Hardware	24	Doors, Frames and Hardware	3	23	No.	75	1	0.900

As shown in table 4 above, each task has a certain location, a fixed quantity, an estimated consumption rate, and requires a certain crew. Activities follow a finish-to-start relationship; an activity has as predecessor the activity just before it. This data is defined in the model through storing it in parameters that characterize each activity agent.

Note that tasks at the actual construction site did not have finish-to-start (FS) relationships only; it had a more complex logic including Finish-to-finish and Start-to-start relationships with delays. However, for this model, logic for push scenario was simplified to have only FS relationships. The reason for this is that the aim of the model is to test project control methods rather than project planning techniques. Thus, variability in the initial plan/schedule were reduced and simplified in order to reveal the true potential of production control techniques on project and crew performance. Therefore, a pull scenario is compared to a well-structured and optimized push one, since a traditional push scenario is even worse than the one considered in this model.

Besides, each task has a planned start and end date. Since activities are assumed to have a FS relationship, actual durations and dates were adjusted as follows:

- Activity durations were taken from actual schedule.
- Dates were calculated based on the finish to start relationship: each activity that has no predecessor preserves its provided start and end date, and then the end date of this activity is the start date of its successor and so on.
- The total duration of the project modeled should be equal to the actual duration of the real project, thus activity durations were multiplied the appropriate factor to achieve this condition.

- Considerations in durations and dates were the same used on the actual schedule. They are as follows:
    - There are 22 working days in a month.
    - There are 8 working hours in a day.

Then during simulation, and while considering push scenario, an activity could be on time, late, or ahead of schedule compared to the preset dates. This is explained in details in “condition generator event”.

Concerning pull scenarios, the same logic (finish-to-start relationship) is used, in addition to ensuring continuity of activities throughout different locations. Thus, a typical task has 2 predecessors, the task just before it in the same location, and the same task in the previous location. Besides, an optimum number of crews is used for each activity to ensure form a well-planned takt schedule.

Going further with the attributes of activities, each task has the parameters described in addition to other attributes that are shown below in Figure 8 below.

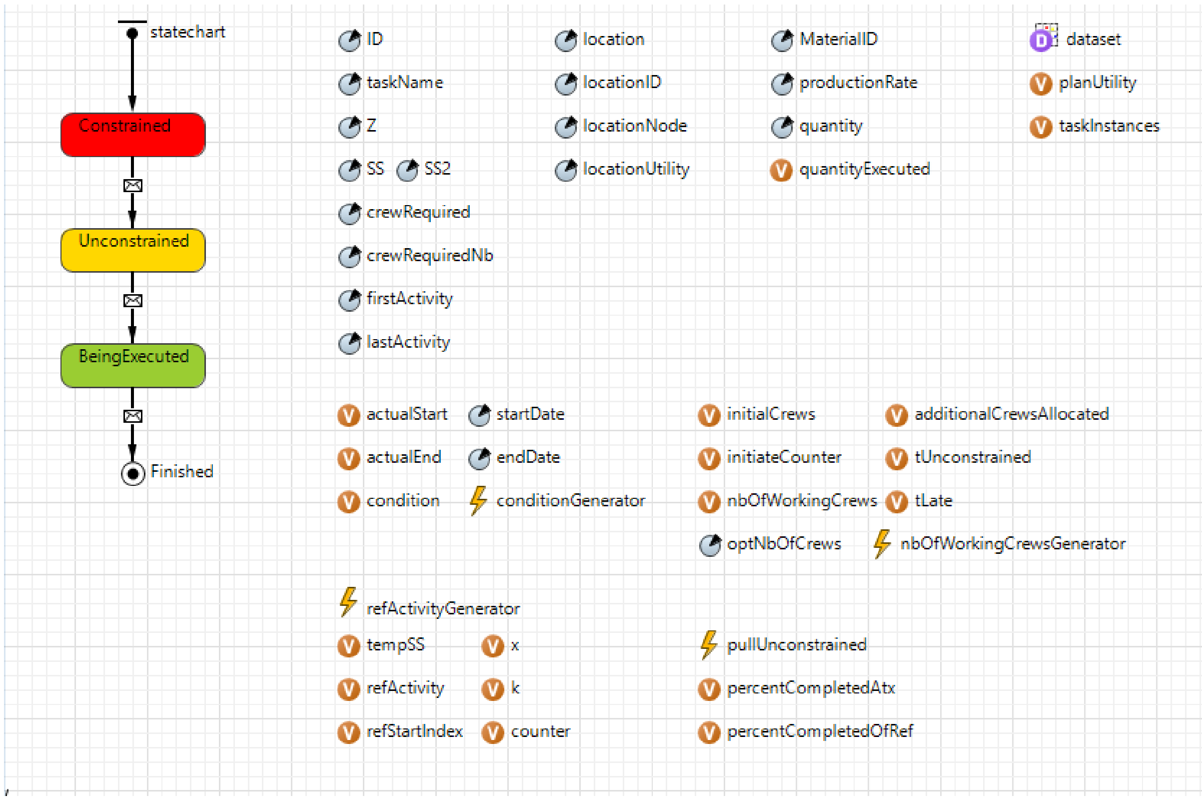

Figure 8 Screenshot of "Activity" agent attributes from AnyLogic

As shown in Figure 8 above, parameters are used to initialize each task giving an ID, name, location details, predecessors, crew required expected production rate and quantity to be executed. Variables are then used to keep track of attributes that change during the simulation time such as quantity executed, actual start and end dates, task's condition, number of crews working on the task, etc. other events such as "Ref. Activity Generator" and "Pull Unconstrained are explained later through this section in details.

The state chart shown in the figure above represents the states that all tasks pass through. These states and transitions between them are described in the Table 5.

Table 5 Behavioral states of "Activity" agents state chart

STATE	DESCRIPTION	TRANSITION PROCESS
CONSTRAINED	An activity is in this state if it is still not ready to be executed (predecessor not finished yet).	Each activity enters the state chart to this state
UNCONSTRAINED	An activity is in this state once its predecessors are finished.	When an activity receives a message "unconstrained" generated by "unconstrained event"
BEING EXECUTED	An activity in this state is being executed by certain crew(s). While a task is in this state, its completed quantity and the productivity of the crew(s) working on it are continuously updated.	An activity moves to this state if it gets the highest utility generated by utility function. In this case, it receives a message "started" that is generated when the crew assigned to it reaches "working" state in Crew agent state chart
FINISHED	An activity is in this state once all the quantity is executed.	Once quantity executed is equal to the total quantity of the activity, the activity agent receives a message "finished".

The methods used in determining an task's condition, whether it is on time, late, or ahead of time differs between push and pull scenarios. This condition is generated through the "condition generator event", which is explained in Table 6 below.

Table 6 Comparison between push and pull scenarios applied to Condition Generator Event

	Push	**Pull**
Task is unconst-rained	When a task is unconstrained, if: • Simulation time < planned start date →early • Simulation time <= 1.1xStart date →on time • Simulation time > 1.1xStart date →late	• If activity stays unconstrained for more than 1 day (8 hrs.), it is late (since it should maintain the continuous line)

	Push	Pull

Task is being executed	When a task is being executed, if:
	• time < start date → early
	• start date <= time <= end date
	    • $\frac{\text{time − start date}}{\text{end date − start date}} > 0.91 > \frac{\text{qtty executed}}{\text{total qtty}}$ →late
	    • $\frac{\text{time − start date}}{\text{end date − start date}} > 1.1 < \frac{qtty\ executed}{total\ qtty}$ →ahead of time
	    • Else activity is on time
	• time > end date → end date exceeded
		• After all activities are “takt” planned, the way they are controlled during execution is as follows:
		    ○ Conditions of all activities are based on the time buffer between the reference activity and the activity considered
		    ○ If time buffer is increasing →late
		    ○ If time buffer is decreasing →early
		    ○ Else →on time
		• This is modeled in AnyLogic in a way that percent of quantity executed of the task considered and that of the reference activity are compared at a fixed time interval, which is determined from start dates of these activities. Then:
		    ○ %completed of activity A < 0.5* % completed of reference activity →too late
		    ○ %completed of activity A < 0.91* % completed of reference activity →late
		    ○ %completed of activity A > 1.1* % completed of reference activity →early
		    ○ Else on time

The reference activity used in determining the condition of each activity (in case of pull scenario) is considered to be the first encountered continuous activity before the activity being studied. The reference activity is determined by “ref Activity Generator” event.

Once aa task is late, the way it is being handled differs between push and pull scenarios. This is clarified in the Table 7 below.

Table 7 Push and pull methods for handling late tasks

Push	Pull

• If a task's condition is "late": send up to 75% of resources/crews to this task
• If an task's condition is "end date exceeded": send all crews except 1 crew to this activity
	• If a task's condition is "late": send crews to this task until reaching the optimum number of crews.
	    • if number of working crews on this task = optimum number of working crews
	    • and if task's condition stays "late" for 2 working days
	Then using "Pull Unconstrained" event, the same task, which is to be executed in the upcoming location, will be unconstrained.

As explained in the conceptual framework, more crews are sent to a late task if push technique is applied, paying less attention to crew productivity. This is translated in the push technique explained in the table above. On the other hand, for pull technique, crews are assigned to a late task until reaching an optimum number after which crews' productivity would be much affected. If these crews could not bring the task to be back on time within 2 days, the same task in the upcoming location will be unconstrained, this way there will be discontinuity in the line of balance in this specific activity, however, the delay in this task will not affect other activities downstream.

After describing the "Activity" Agents, the following sub-section presents "Location" agents.

3. Location Agents

This agent population includes all location of the project whereby crews move and work on activities. The main attributes of this agent are the location ID, name, floor, area, number of crews working in it, and the percent congestion. The locations are defined and along with their attributes according to Table 8.

Table 8 Project locations and their attributes

LOCATION NUMBER	ID	AREA	FLOOR	SIZE (m^2)
1	SE1	Southeast	1	1540.4
2	SE2	Southeast	2	1540.4
3	SE3	Southeast	3	1540.4
4	SER	Southeast	4(Roof)	1540.4
5	SW1	Southwest	1	1831.7
6	SW2	Southwest	2	1831.7
7	SW3	Southwest	3	1831.7
8	SWR	Southwest	4(Roof)	1831.7
9	NE1	Northeast	1	1788.9
10	NE2	Northeast	2	1788.9
11	NE3	Northeast	3	1788.9
12	NER	Northeast	4(Roof)	1788.9
13	NW1	Northwest	1	1392.6
14	NW2	Northwest	2	1392.6
15	NW3	Northwest	3	1392.6
16	NWR	Northwest	4(Roof)	1392.6
17	C1	Center	1	337.5
18	C2	Center	2	337.5
19	C3	Center	3	337.5
20	CR	Center	4(Roof)	337.5

4. Main Environment: Construction Project

The main environment includes all the agents, parameters, functions and events required to initialize the model and run it in a rational manner. It represents the construction site where all agents interact with each other. Figure 9 displays a screenshot from AnyLogic showing the main attributes of “main” agent.

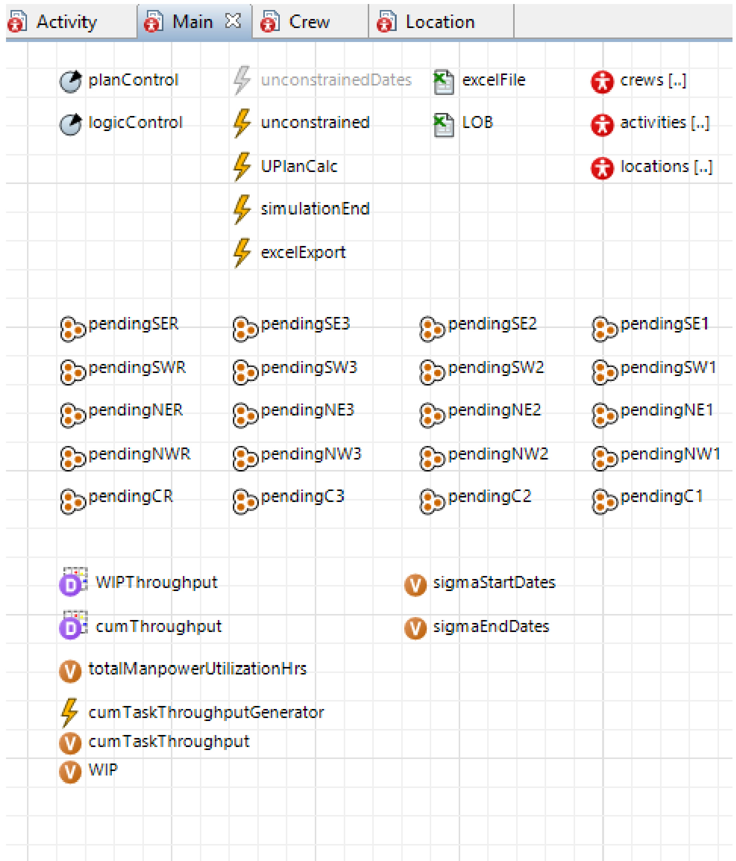

Figure 9 Screenshot of main environment from AnyLogic

Figure 9 shows the events following main events:

- "Unconstrained" event, which unconstrained tasks based on certain conditions. This event is further explained through this sub-section.
- UPlanCalc: this event calculates U_{Plan} factor that is used in the utility function. This event was explained in this chapter.
- CumTaskThroughputGeneraor: this event calculates one of the metrics used for the evaluation of push and pull techniques. This metric is task throughput. It is explained with other metrics in the chapter that follows.

Besides, the set of “collections” shown track unfinished (pending) tasks in each location. Other parameters, variables and datasets shown are used to keep track of metrics (such as WIP, summation of start and end dates…) that are explained later in the chapter that follows.

Going back to tasks, they become unconstrained and ready to be executed based on the following event that is cyclically generated.

a. Unconstrained Event:

This event makes tasks unconstrained based on certain conditions that differ between push and pull scenarios. Table 9 describes these conditions.

Table 9 Unconstrained event applied in push and pull scenarios

Push	**Pull**
Each task that has no predecessor (first activity in each location) is unconstrained on its planned start date, and then tasks that follow in the same floor are unconstrained based on the finish to start relationship; a task is unconstrained if its predecessor is finished.	The same conditions of push apply here in addition to enforcing continuous lines of balance through adding a finish to start relationship between tasks at different locations and belonging to the same activity. Note that the only task with no predecessors is the first task in the first location (first tasks in other locations are related to tasks of the same activity in previous locations.)

After describing each agent along with its main attributes, the following summarize how these agents work and interact within the main environment. At first, all agents' parameters are initialized. Then unconstrained function detects tasks that can be executed, once a task(s) is unconstrained, random number of crews (between 1 and 3) are directly sent to the construction site, where each crew runs the utility function, and moves to the activity having the highest utility. This scenario applies to all activities and all crews. Throughout the simulation time, many tasks would be in the execution phase, and multiple crews would be working in the same location. This may cause congestion, which may reduce crews' productivity. Besides, once an activity gets late, it is handled either by allocation more crews (in push scenario), or by other methods such as un-constraining the similar task that follows in the upcoming location (in pull scenario). Different incidents that happen throughout execution, and different ways used in production control may lead to unexpected multiple complex scenarios that are very different from the plan.

Then in order to determine and compare production control techniques based on certain criteria, some metrics, which help in evaluation, have been set. This is explained in details in the Results section.

CHAPTER 6

APPLICATION OF THE MODEL

A. Model Verification and Validation

1. Model Verification

To verify the model, extensive testing was performed to assure that “we built the model right”. Coding manuscripts and functions were closely checked. Temporary parameters and variables were used to trace different functions and events used in the model and verify that they are correctly used. Besides, a software and coding specialist was consulted for advanced coding checked and verification.

2. Model Validity

In order to know if we built the “right model”, several validation techniques, stipulated by Sargent (2005), were used:

Animation tests: the model operational behavior was validated through the visualization of crews’ movement from one location to another on the construction site as the model runs. Besides, lines of balance were displayed and updated every working day, and a reasonable relation could be drawn from the number of crews working in a location and the slope of the LOB of the corresponding task; more crews working show steeper slopes representing higher production rates. Besides, the level of congestion in locations was monitored as it showed harmony with different number of crews working in the same location.

Face Validity: experts who are knowledgeable about real production planning and control systems have been consulted. Dr. Olli Seppanen, professor of Practice at Aalto University, Finland, and planner at Al Camino Medical Office Building project, California, USA has been consulted to evaluate conceptual model and its rationale, in addition to data input and results.

Internal Validity: several simulation runs with stochastic behavior showed acceptable variability. Results of metrics that were measured had acceptable standard error values (less than 0.01) within less than 50 runs.

Operational Graphics: Different metrics and variables were dynamically tracked throughout simulation runs. Quantity executed of each task, congestion in each location, idle time, productivity, task conditions (late, on time, etc.) and number of crews working at the same location were updated continuously (every hour) in order to keep data realistic and be used correctly in functions and events. These metrics and variables were tracked each on its own and along with each other in order to reach a realistic and logical behavior of the model. For example, the number of crews working in a location and the level of congestion show a direct relation as they increase and decrease with each other throughout simulation time. Another case is determining the reference activity visually from the LOB that is being dynamically updated and, which shows the same reference activity determined by the model functions. Besides, concerning a task's condition in a pull scenario, the percent completion of a task in was visually related to that of its reference activity, at a fixed time interval, and it showed consistency whereby a late task had less percent completion than its reference task and so on.

3. Validation of Inputs

Appropriate data from an actual construction site were used for model initialization; the project considered is “Camino Medical Office Building” located in Mountain View, California, USA. It is a 250,000-sq.-ft., three-story medical office building mainly housing physician offices, exam and procedure rooms. Data includes the needed information to build the model, such as crews along with their attributes (example: number of crews and their types), activities and tasks (including their quantities, consumption rates, required crews, locations etc.), site layout, exact areas of locations, etc.

B. Simulation Experiments

The model experiments aim at studying and comparing two different techniques used in production control, indicated by push and pull techniques. The model is simulated 70 times for each case/technique (push and pull), so that result attained good consistency, reaching a total of 140 runs. The model inputs, which include characteristics of all tasks, crews and locations, are constant for all simulation runs; expected labor productivity, maximum number of crews, tasks quantities and expected durations, in addition to other attributes, are all fixed. What varies is the way this schedule is applied on site, resembling a real case scenario, and the conditions that arise during project execution. For example, even though the maximum number of crews provided by the subcontractor is fixed, the “available” number of crews that could work on this project at a certain time varies from one simulation to another, or even within the same simulation run, assuming that the “subcontractor” may have different sets of projects and different ways of resource allocation and balancing between projects. Functions and events that make the model stochastic are summarized below in Table 10.

Table 10 Functions and events that make the model stochastic

Function / Event	Description
Mobilization Delay	This represents the delay before a crew reaches the construction site. Mobilization delay is assumed to be a random number having a mean value 1 week.
Resource Allocation function	Once a task is unconstrained, a random number of crews between 1 and 3 is sent directly to this task. Besides, when a task is late, a random number of crews (between 1 crew and the required number of crews) is sent to the construction site, assuming that a subcontractor may not have all crews (that were required) available for this project.
Plan Utility Calculation Event	It is used to calculate plan utility for each task. This event runs randomly at an average rate of 1 time/ working day.
Unconstrained Event	Used for un-constraining tasks. This event runs randomly at an average rate of 1 time/ working day.

Randomness in these functions and events make the model more realistic though bringing out the uncertainty that appears in real construction projects. It leads to allocating different number of crews to tasks, shifting tasks' status from being on time to being late, or even early, changing the level of crowdedness and thus altering crews productivity, in addition to many other behavioral actions and reactions, which make the model approach as much as possible a real construction site.

After setting up the model, simulation experiments are generated and different metrics are collected from each run to help in comparing the two production control techniques (push and pull). These metrics are summarized in table 11.

Table 11 Metrics used for comparison between push and pull scenarios

Metric	Description	Equation
Project total duration (working days)	Duration required to finish all activities of the project	$\frac{model\ time\ at\ end\ of\ simulation\ (hrs)}{8(working\ hrs/day)}$
Total Manpower working time (working days)	Summation of working time of all crewmembers during the project duration	$\sum_{all\ crewmembers} working\ time\ throughout\ project\ duration$
Summation of activities' Start Dates (hrs.)	Summation of all activities' start dates	$\sum_{all\ activities} start\ dates$
Summation of activities' End Dates (hrs.)	Summation of all activities' end dates	$\sum_{all\ activities} end\ dates$
Task Throughput (nb of tasks)	Number of finished tasks at a certain point of time	$\sum finished\ activities\ at\ certain\ simulation\ time$
Total Idle time/crew (hrs.)	Total duration during which a crew is in the idle state	$\sum model\ time\ when\ leaving\ idle\ state - model\ time\ when\ entering\ idle\ state$
Productivity (units/hr/crew member)	Quantity executed by each crewmember during a time interval	$\frac{quantity\ executed\ per\ a\ crew\ member}{time\ interval}$

Turnover rate (locations visited/time unit)	Frequency of a crew changing locations per unit of time (it includes re-entering to the same location)	$\frac{locations\ visited\ per\ crew}{time\ interval}$
Task Instances (nb of tasks)	Number of interruptions of each task	$\sum_{all\ tasks}$ (instances having no crews working on a task that is in "being executed" sta
WIP (nb of tasks)	Unfinished activities at a certain point of time	$\sum \frac{WIP}{at\ certain\ model\ time}$

Each metric explained in Table 11 above sheds light on certain aspects that help in assessing the production control technique used, be it push or pull. Project duration metric shows which technique gives a shorter construction time. Total manpower working time indicates which technique works better in terms of cost; a scenario through which the project finishes with less working time shows that it has utilized less human resources, and thus less associated labor rates have been paid (note that since materials are considered continuously supplied to the construction site, and no material consumption is being tracked, material costs is not being compared between the two scenarios).

Moving to summations of activities start and end dates, it shows a relation between staring end ending times of activities in a way that starting early may not lead to finishing early. Other metrics such as task throughput and WIP show an average pace at which tasks are being completed, besides the quantity of uncompleted work at certain points of time during project execution. Moving to idle time metric, it gives an idea on the wasted time of crews on the construction site. In addition, one of the main metrics is productivity; it explicitly shows the effect of both production control techniques on this metric.

Turnover rate shows how many locations each crew visits throughout a certain period. A larger turnover rate is considered to produce larger non-value-adding movements; time wasted for physically moving from a location to another, time associated with material procurement to these locations, and the effect of work discontinuity on productivity are considered to produce waste. Task instances show how many times a task started/stopped during a certain period. It is similar to turnover rate; however, instead of focusing on the crew to capture work discontinuity, it focuses on the task.

After describing the metrics to be measures from each run, Table 12 shows the summary of the output results generated from a total of 140 runs.

Table 12 Summary of the output results generated from a total of 140 runs

Metric	Notes	Push Runs (mean values)	Pull Runs (mean values)
Project Duration (Working Days)		376.83	390.46
Total Manpower Working Time (Working Days)		8117.49	5632.58
Sum. Activities Start Dates (hrs.)		17459.90	17869.09
Sum. Activities End Dates (hrs.)		55028.61	50980.82
Task Throughput (nb of tasks finished/working day)	Mean	0.97	0.93
	STD	0.97	0.98
Average Idle Time / Crew Type (% idle time of overall time being on site)	Casework	27.91	24.39
	Ceiling Tile	27.77	24.40
	Doors, Frames and Hardware	41.98	34.50
	Drywall	34.50	30.41
	Electrical	17.74	15.53
	Fire Sprinkler	14.49	10.32
	Flooring	25.15	22.75
	Mechanical	25.26	23.44
	Painting	19.21	15.80
	Plumbing	26.83	19.66

Metric	Notes	Push Runs (mean values)	Pull Runs (mean values)
	Specialties	38.92	31.34
Average Productivity / Crew Type (units/hr./crewmember)	Casework	3.55	4.90
	Ceiling Tile	64.22	92.24
	Doors, Frames and Hardware	1.11	1.22
	Drywall	47.27	62.89
	Electrical	7.61	11.05
	Fire Sprinkler	14.29	15.51
	Flooring	36.33	49.49
	Mechanical	5.10	7.50
	Painting	102.11	114.83
	Plumbing	16.11	18.46
	Specialties	5.00	5.00
Average Turnover / Crew Type (number of places visited throughout the project duration by a crew)	Casework	31.26	15.42
	Ceiling Tile	49.25	17.78
	Doors, Frames and Hardware	14.64	5.81
	Drywall	49.85	27.21
	Electrical	121.08	72.59
	Fire Sprinkler	61.31	27.36
	Flooring	31.80	19.99
	Mechanical	94.20	53.23
	Painting	55.32	44.39
	Plumbing	53.65	24.79
	Specialties	21.64	9.97
Task Instances (interruptions/ 100 tasks)	Mean	88	2
WIP	Mean	5.93	5.26
	STD	2.53	2.70

CHAPTER 7

ANALYSIS AND DISCUSSION OF RESULTS

A. Analysis of Simulation Experiments' Results

Several hypotheses concerning the effects of push and pull techniques on different project performance metrics were set, then simulation outputs were collected from each run. The collected data was tested for normality using a significance level of 5%, results showed that data followed a normal distribution. Test results are aligned with the Central Limit Theorem, which considers that if a samples' size is relatively large (>30), the data could be assumed to follow a normal distribution. Hence, "Student t-test" was conducted to compare the samples (i.e. push vs. pull) for each response considering a 5% significance level. Hypotheses and their results are described in Table 13.

Table 13 Hypothesis testing for every metric

Response		Hypothesis	p-value	Results
Project Duration		H_0: μ(pull)- μ(push) ≥0 H_a: $\Delta > 0$	1	Pull>Push
Total Manpower Working Time		H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
Sum. Activities Start Dates		H_0: μ(pull)- μ(push) ≤ 0 H_a: $\Delta > 0$	8.717e-13	Pull>Push
Sum. Activities End Dates		H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	1.158e-10	Push>Pull
Task Throughput	Mean	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	8.605e-07	Push>Pull
	STD	H_0: μ(pull)- μ(push) ≤ 0 H_a: $\Delta > 0$	0.07244	
Average Idle Time / Crew Type	Casework	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	7.25e-08	Push>Pull
	Ceiling Tile	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	4.063e-09	Push>Pull

Response		Hypothesis	p-value	Results
	Doors, Frames and Hardware	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Drywall	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Electrical	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Fire Sprinkler	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Flooring	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	0.0001654	Push>Pull
	Mechanical	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	3.167e-12	Push>Pull
	Painting	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	1.403e-09	Push>Pull
	Plumbing	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Specialties	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
Average Productivity / Crew Type	Casework	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Ceiling Tile	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Doors, Frames and Hardware	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	1.314e-05	Pull> Push
	Drywall	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Electrical	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Fire Sprinkler	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Flooring	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Mechanical	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Painting	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Plumbing	H_0: µ(pull)- µ(push) ≤ 0 H_a: Δ > 0	< 2.2e-16	Pull> Push
	Specialties	Identical Vectors		
Average Turnover / Crew Type	Casework	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull
	Ceiling Tile	H_0: µ(pull)- µ(push) ≥ 0 H_a: Δ < 0	< 2.2e-16	Push>Pull

Response		Hypothesis	p-value	Results
	Doors, Frames and Hardware	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Drywall	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Electrical	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Fire Sprinkler	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Flooring	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Mechanical	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Painting	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Plumbing	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	Specialties	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
Task Instances	Mean	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
WIP	Mean	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta < 0$	< 2.2e-16	Push>Pull
	STD	H_0: μ(pull)- μ(push) ≥ 0 H_a: $\Delta > 0$	1	Pull> Push

It could be noticed from Table 13 above that, for some metrics, data show a null hypothesis and an alternative one for each type of crews, since metrics were measured for each crew and then an average value was calculated for each set of crews of the same type. Besides, since crews witnessed the close p-values and same results for each metric, general hypotheses can be concluded for all crews. This is summarized in Table 14 below.

Table 14 Generalized hypothesis and their results

Metrics		Null Hypothesis	Results	Significance Level
Project Duration		Project duration in push scenario is less than that in pull scenario	Accepted	5%
Total Manpower Working Time		Total manpower working time in a pull scenario is greater than that in push scenario	Rejected	5%
Sum. Activities Start Dates		In general, activities in pull scenario start earlier than in push scenario	Rejected	5%
Sum. Activities End Dates		In general, activities in push scenario finish earlier than in pull scenario	Rejected	5%
Task Throughput	Mean	Tasks are being completed at a slower pace in push than in pull scenario	Rejected	5%
	STD	Variability in task throughput in push is less than that in pull	Rejected	10%
Idle Time		Crews spend more time idle in pull more than push scenarios	Rejected	5%
Productivity		Crews are more productive in push rather than pull scenario	Rejected	5%
Turnover		Crews change locations more in a pull scenario rather than a push one	Rejected	5%
Task Instances	Mean	Tasks in pull scenario are interrupted more often than in a push scenario	Rejected	5%
WIP	Mean	WIP in a pull scenario is higher than that in a push scenario	Rejected	5%
	STD	WIP in pull varies more often than in a push scenario	Accepted	5%

The hypothesis and results presented in Table 14 above are explained in the following sub-sections.

a. <u>Project duration and Lines of Balance:</u>

Project duration is expected to be shorter in push scenarios as planning focuses on starting tasks ASAP. However, considering a pull scenario, project duration could be enhanced if a pull “takt” plan is optimized through assigning an appropriate takt to be followed for activities and reducing time buffers. In this case, the considered pull scenarios started from an optimized pull “takt” plan.

It could be noticed that, on average, project duration was shorter in push scenarios than that in pull ones. However, the difference in average project durations between push and pull techniques was around 14 working days (376 working days in push scenario and 390 working days in pull scenarios). In other words, pull technique showed an increase in the project duration by 3.7%, which is considered as a minor difference in reference to the project durations.

One of the main reasons for push scenarios having shorter project duration is that in a pull scenario, the reference activity, which is used to tell if an activity is late, early or on time, is considered to be the first encountered continuous activity before the activity being studied. Thus, if the reference activity for some reasons was late and then had a milder slope than the activity before, this will lead to delaying the activity after it accordingly, and if this activity was also delayed (keeping a continuous LOB), delays in following activities downstream could accumulate leading to an overall larger project duration.

Thus, even though ensuring continuous Lines of Balance ensures constant productivity, it could have some negative effects; each continuous activity is a reference for the one after, and if each activity is delayed keeping a continuous line, the activity after may have a reduced production rate (milder LOB slope), bringing an unnecessary delay to the whole project. This delay could increase from one activity to the other as we move through activities downstream, forming a “bullwhip” effect.

The Line of Balance displayed in Figure 10 below shows the LOB of a pull representative run. A separate legend for the graph is shown in Figure 11. It could be noticed that there is continuity in the lines of balance for the majority of activities, which means that once crews finish working on a specific task in a location, they continue to work on the same task taking place in the upcoming location.

Note that not all crews will move to the same task; it depends on the utilities/scores generated by the utility function, which determines which is the most suitable task for each crew based on the schedule, anticipated productivity in the new location, and proximity between the current location and the new one. So for example, few crews might move to a new location that has a high utility, and once other crews generate the utility function, conditions may be changes making another task have a higher utility (reasons may be the level of congestion that would affect their productivity after moving to the location, the conditions of other activities that may be late thus requiring additional crews to be back on time, etc.).

Besides, if we consider an activity's line of balance, we could notice that it may have sharp or mild slopes at different times. The slope represents production rate; steep slopes mean high production rate and vice versa. As explained earlier, the reference that determines what are "steep" or "mild" slopes is the comparison with the slope of the first encountered continuous activity before it. If the slope is milder, then the activity is becoming late and more crews (up to the maximum allowable number of crews) are allocated to get the back to its track. If this task could not get back to the required production rate within 2 working days, the upcoming task in the following location is unconstrained (breaking in this case the continuity of LOB) in order to avoid delaying other activities downstream.

Note that few activities did not have continuous lines of balance, since it has small quantities to be executed and relatively high productivity for crews working on it. For example, “Cable Tray” task, taking place in “Central Location” in the first floor, requires installing 50 lf (linear foot) of cables trays at a consumption rate of 0.053 hr./lf, which means 1 crew (composed of a single individual) is able to finish this task within 2.65 hrs., that is about one-third a working day (8 hrs.). This makes its LOB’s slope very steep and thus cannot follow the “milder” slope of its reference activity.

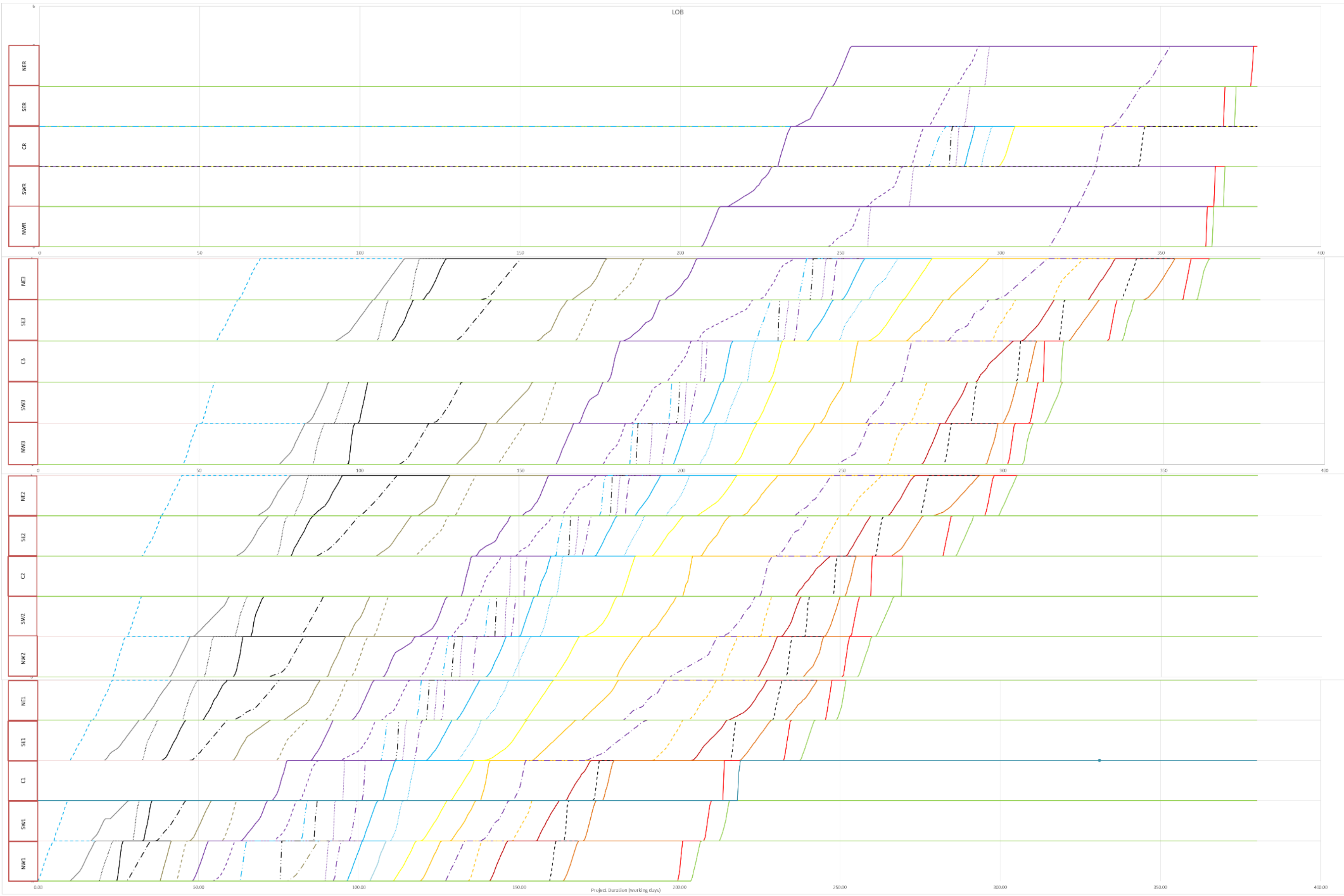

Figure 10 Line of Balance of a representative pull run

Crew ID	Crew	Activity	LOB color and linetype
1	Casework	Casework, Millwork	
2	Ceiling Tile	T-Bar	
		Ceiling tile	
3	Doors, Frames and Hardware	Doors & Hardware	
4	Drywall	Drywall	
		Frame priority fullheight walls etc.	
		Tape and Finish	
		Top track, beam clamps, etc.	
		Wall, Hard Ceiling, and Soffit Framing	
5	Electrical	Branch conduit	
		Feeder conduit	
		Cable Tray	
		Light Fixtures, Diffusers, Ceiling Mounted Trim	
		Tele/data, Nurse Call, Security, AV, and Fire Alarm	
6	Fire Sprinkler	Sprinkler Rough	
7	Flooring	Floor coverings	
8	Mechanical	Medium pressure duct	
		Mechanical Rough	
		VAV and Low Pressure Ducts	
		Wall, Hard Ceiling, and soffit MEP Roughins	
		MEP Trim	
9	Painting	Paint	
10	Plumbing	Domestic Water	
		Rain Water Leaders, Waste and Vent	
		MED GAS	
11	Specialties	Specialties and accessories	

Figure 11 Legend for Line of Balance Graphs

Now considering a Line of Balance for a representative push scenario, which is shown in Figure 12. It could be noticed that there is no continuity in LOBs of activities. Some examples of discontinuity are indicated by pointers in Figure 12. Tasks witness multiple interruptions due to the fact that if a crew was working on a task that is early or on time and another task becomes late, this crew may move to that task (depending on the utilities of those tasks), which leads to a break/interruption in the current task (shown as horizontal line in the LOB of this specific task). So, since many crews are allocated to a late activity (making its production rate high and thus its LOB's slope steep), and since activities are not continuous (a task can start directly after its predecessor in the same location finishes, without waiting the same task at the previous location to finish), the overall duration of the project was shorter than pull scenarios.

It is important to point out at this stage that the push scenario considered in this model is considered to be an optimized push scenario. In other words, push scenarios taking place in actual construction projects are "worse" than the push case considered here; tasks relationships are more interconnected which makes a delay in a task affect more than one task. Besides, different tasks could be executed simultaneously in the same location leading to trade-stacking, which further reduces crews' productivity affecting the overall project duration and crews behavior.

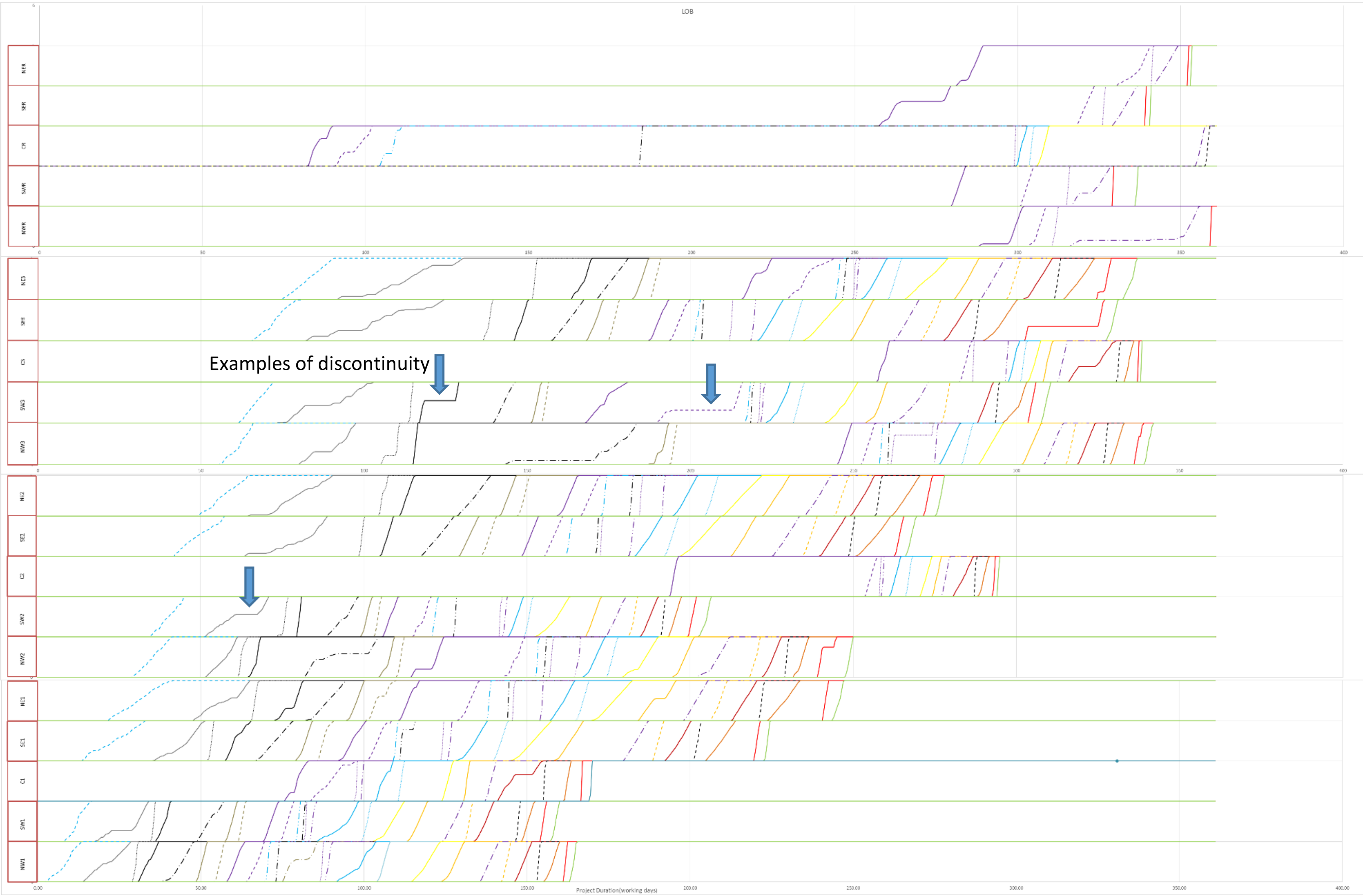

Figure 12 Line of Balance of a representative push run

b. Total Manpower Working Time and Labor Costs:

The total manpower working time is the summation of the working time for all crews throughout the whole project. It was noticed that on average, crews worked cumulatively 8118 hrs. in push scenarios, whereas they only worked for 5633 hrs. in pull scenarios. This shows a difference of 2485 hrs. This is mainly due to the increased productivity of crews in pull cases; crews may be allocated to late activities in a push scenario regardless of the level of congestion they cause and its effect on productivity. Decreased productivity makes each crew work more time to generate the same amount of work. Thus, the summation of all crews' working time would be higher in pull than push scenarios.

The change in manpower working time affects project costs. The more crews work, the their incurred cost will be and visa versa. Push and pull techniques resulted in different manpower working time that was required to finish the project. This gives an indication to labor cost change between these two scenarios. For simplicity, assume an average wage (x dollars/hr) for all crews, this means that adapting a pull scenario indicates a decrease labor costs by:

$$\boldsymbol{Labor\ Cost}\ indicator = \frac{\mathbf{5633}\boldsymbol{x} - \mathbf{8118}\boldsymbol{x}}{\mathbf{8118}\boldsymbol{x}} \times \mathbf{100} = -\mathbf{30.6}\% \approx -\mathbf{30}\%$$

Equation 5 Labor cost indicator

The graph displayed in Figure 13 shows the percentage decrease in labor costs through different simulation runs.

Figure 13 Percent Decrease of labor costs in pull scenarios compared to push scenarios

It could be noticed that throughout all simulations, labor cost decreased from push to pull scenarios by a range varying from 29% to 31%.

Comparing this metric to project duration metric, it could be said that labor cost is expected to be less in pull scenarios than in push ones, however, project might require a longer duration to finish. This suggests that depending on the actual status of the project, a combination of push and pull techniques could be used to for production control. Push could be applied when a project is late, whereas pull is used to handle a project that is going (or expected to go) over budget. This is even broken down to be applied at the level of activities, where a late activity can be pushed at certain times, and another early or on time activity could follow a pull technique to avoid getting over budget.

c. Summation of Activities' Start and End Dates:

The summation of start dates of all activities for all runs is shown in Figure 14. It shows that on average, activities in push scenarios start earlier than in pull scenarios. This is because activates, in a pull scenario, do not start as early as possible, but stay till the last responsible moment. To be more specific, a task in the first location – North West Floor 1 (NW1) – do not necessarily start immediately after its predecessor finishes, it is delayed to the time by which if it starts, it could maintain a continuous line of balance.

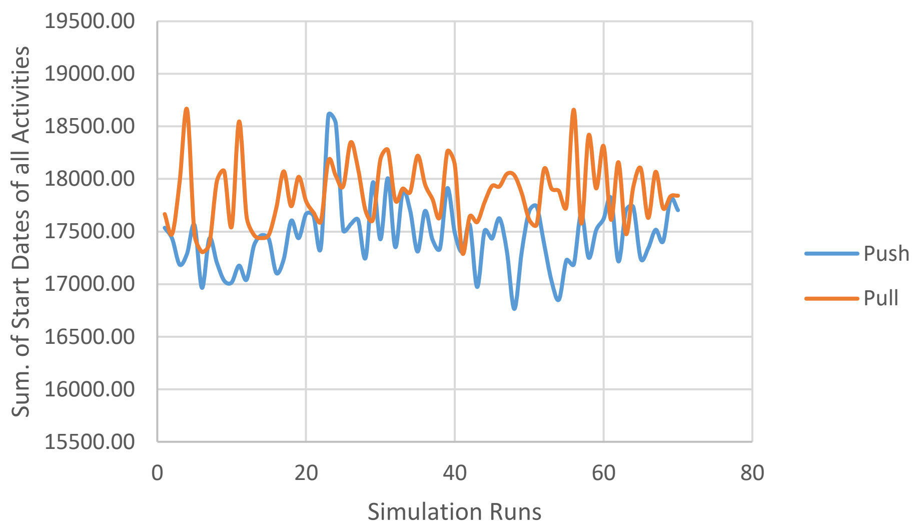

Figure 14 Summation of Start Dates

Concerning end dates of activities, summation of end dates of all activities for all runs is shown in Figure 15.

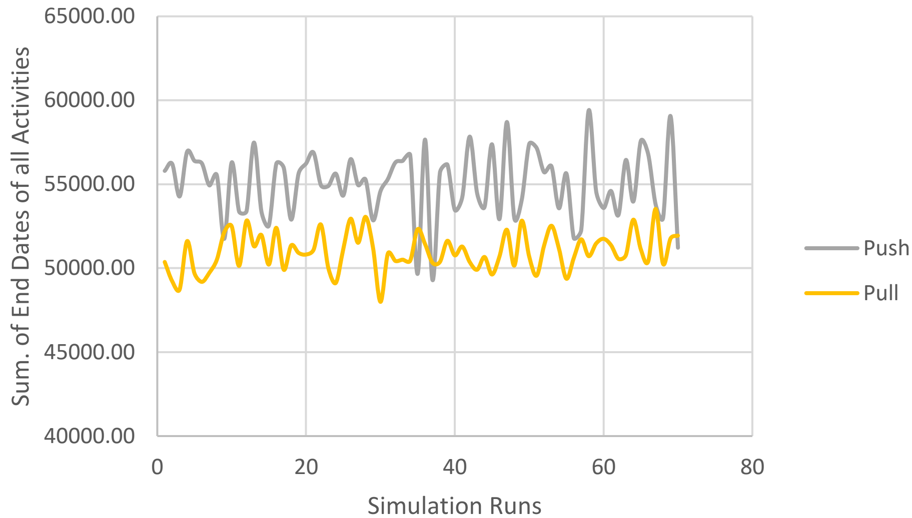

Figure 15 Summation of End Dates

It could be noticed that activities in pull scenarios finish earlier than those in push scenarios. The reason behind this is that in a push scenario, most of the activities tend to finish by the end of the project, making the sum of all end dates a large value. Whereas in a pull scenario, even though the total duration of the project is longer than that in a push scenario, activities are more spread throughout the project duration. In other words, some activities finish early throughout the project lifespan and others finish later, making the total of all end dates smaller than that in a push scenario.

Thus, results of both metrics show that starting activities as early as possible, which is one method of push applications in production control, does not necessarily mean finishing them early. On the contrary, staring an activity at the last responsible moment not only leads to finishing it earlier, but also allows for continuity of its tasks throughout different locations of the project.

d. Productivity:

In general, the productivity of crews had improved once moving from push to pull scenarios. The percentage increase in productivity is shown in Figure 16 below.

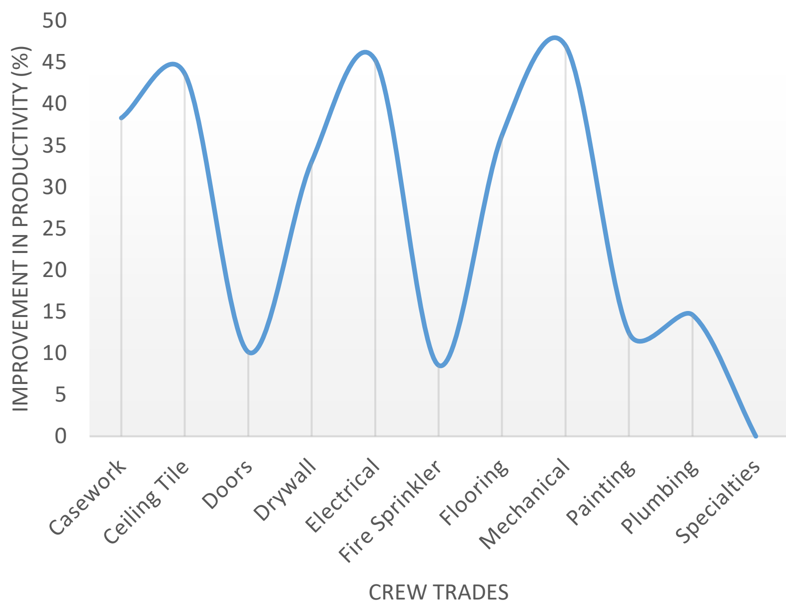

Figure 16 Improvement in the average Productivity of all crew types from push to pull scenarios

As described earlier, productivity is affected by the level of overmanning in the location; more crews working together means less productivity of each of them. In cases of push, the allowable number of crews working together on the same task is much higher than that in a pull case. Thus, in case of a late task, many crews would be working together leading to increased reduction in crews' productivities. Whereas in pull cases, even though an activity is late, there are more restrictions to avoid extreme cases of overmanning, meaning fewer crews are allowed to work in one location. Therefore, productivity is not less affected in a pull scenario compared to a push one.

Besides, crews' productivities improved at different rates; some crews such as "ceiling tile", "electrical" and "mechanical" showed high improvements (up to 47%) whereas other crews only by 10% such as "doors" and "fire sprinklers". The difference in productivity increase is linked to the number of crews in each type of crews. Crew sets having high number of crews showed higher improvements. This is because in cases of push whereby late activities required many crews to be working together, crew types having many resources (such as electrical and mechanical activities) witnessed high productivity reduction due to the high level of overmanning. Whereas other crew types with less human resources could not reach the same level of overmanning. This is reflected on the different levels of improvement for different crew types.

In addition, "specialties" crew did not show any change in productivity between push and pull scenarios because there is only one crew of this type, so there is no possibility for overmanning. Note that the type congestion that affects productivity is overmanning and not trade stacking, because of the finish-to-start relationship between activities that does not allow crews of different types work together.

e. Idle Time:

This metric measures the duration through which a crew is idle on the construction site. Note that idle state may not be the same on real construction sites. Crews would not be on site waiting with nothing to work on, they would not show that they are idle, however actually they are not producing anything adding value. This is explicitly clarified in the model through separating this phase from working state and making it as isle state.

The percentage of time being idle for each crew for all simulation runs (push and pull scenarios) is calculated, and an average value for each set of crews is shown in Figure 17 below.

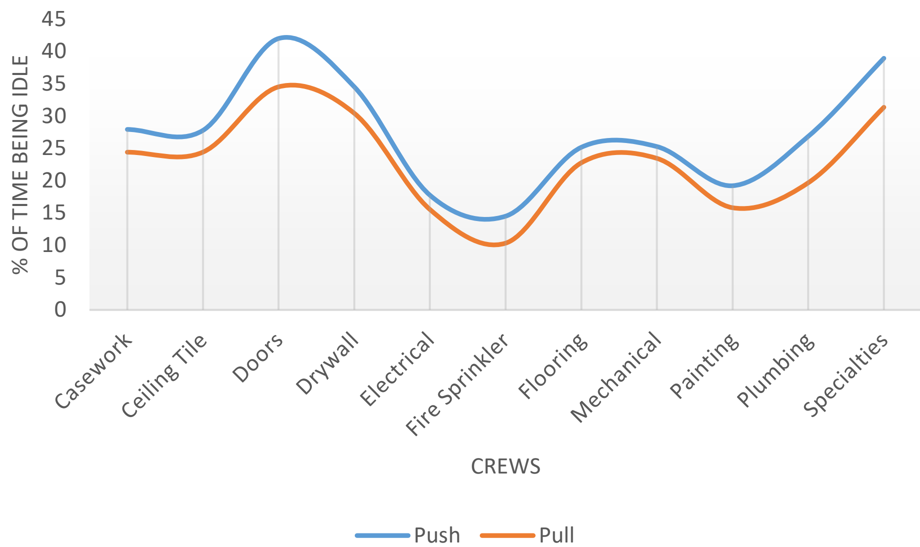

Figure 17 Average idle time for all crew types

It could be noticed that in pull scenarios, crews spend less time being idle. This is mainly due to the continuity of tasks between locations in a pull scenario. For example, consider a pull scenario whereby a crew finishes working on a task, this crew has higher probability finding another task to work on, one of them is the same task in the following location, thus this crew would not spend much time idle. This is shown clearly in the Line of Balance presented previously in Figure X, whereby many tasks start immediately after the same task in the previous location finishes and thus crews work in a continuous manner. Whereas in a push scenario, a crew that finishes a task might not find another task to work on (at least the same task in the following location that has a low probability of being unconstrained and ready to be executed) and thus has to wait for one day being idle before leaving the site (if no other activity becomes unconstrained).

Besides, different crews had different percentages of their time being idle, having the same behavior (trend) in push and pull scenarios. Percentage of idle time depends on different factors, such as the number of tasks required by each type of crews, and the level of closeness of the execution time for these tasks. These 2 factors are not mutually exclusive. This is illustrated through considering examples of crews having different idle time percentages such as “Doors” and “Electrical” crews (doors crews have high percentage of time being idle whereas electrical crews had much less percentage). Only one activity composed of 19 tasks is allocated to “Doors” crews, whereas 5 activities having a total of 95 tasks are assigned to “Electrical” crews. Assume a case where a task is late and many crews are working on it, once it becomes back on time, additional crews would leave the task going back to idle state to look for other activities/tasks (if no activities/tasks are available within 1 working day, the crew would leave the site). In such a case, electrical crews would have higher probability of finding another “concurrent” task to work on, thus it would not be spending much time being idle.

f. <u>Turnover Rate:</u>

Turnover rate shows how many locations each crew has visited throughout the project lifetime. This metric is measured for each crew in every simulation run, and an average value for each set/type of crews is presented in Figure 18 below.

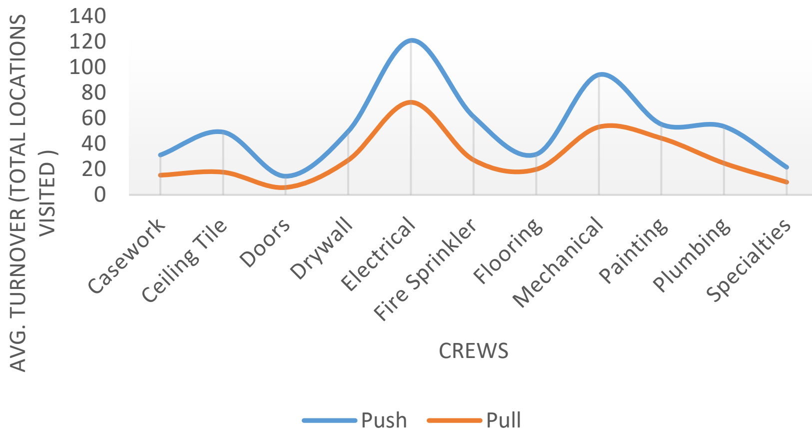

Figure 18 Average turnover for all crew types

As shown in Figure X, crews changed more locations in push scenarios than in pull ones. This is mainly linked to the approaches used to handle late activities. In cases adapting push techniques, a late activity is handled through allocating more crews to it, thus crews working on activities having less utilities (activities that are early or on time) will move to the late task, and once it is on time again, they leave it to another activity that became late and so on. Whereas in pull scenarios, there is a limit to the number of crews that can work on a late activity. This reduces crews' turnover accordingly, since a late activity having the maximum allowable number of crews working on it will not have a high utility anymore and crews would not move to it.

Besides, different types of crews had varying turnover rates. This is related to the number of tasks allocated to each type of crews and the time span between executions of these tasks. The more tasks allocated to a crew and the higher the probability of having tasks being executed simultaneously, the higher the chance for crews to move from a task to another.

In addition, it could be noticed that turnover rate is related to idle time of crews; crews having high turnover rates had lower idle times (such as electrical crews) since they had more options (tasks to work on) and higher probability of tasks having higher utilities than the tasks being executed and thus the chances of changing locations were higher. Whereas crews having low turnover rates had higher idle times (such as doors and flooring crews) due to the limited options they had while being idle.

g. Work in Progress (WIP):

Work in Progress (WIP) is measured by counting the number of activities being executed at the end of each working day. In order to analyze WIP and compare it in push and pull scenarios, representative simulation runs are selected based on the average value of WIP and its standard deviation for the selected run, and the average of all runs together. Figure 19 below shows the change in WIP as a function of time for 2 representative push and pull scenarios.

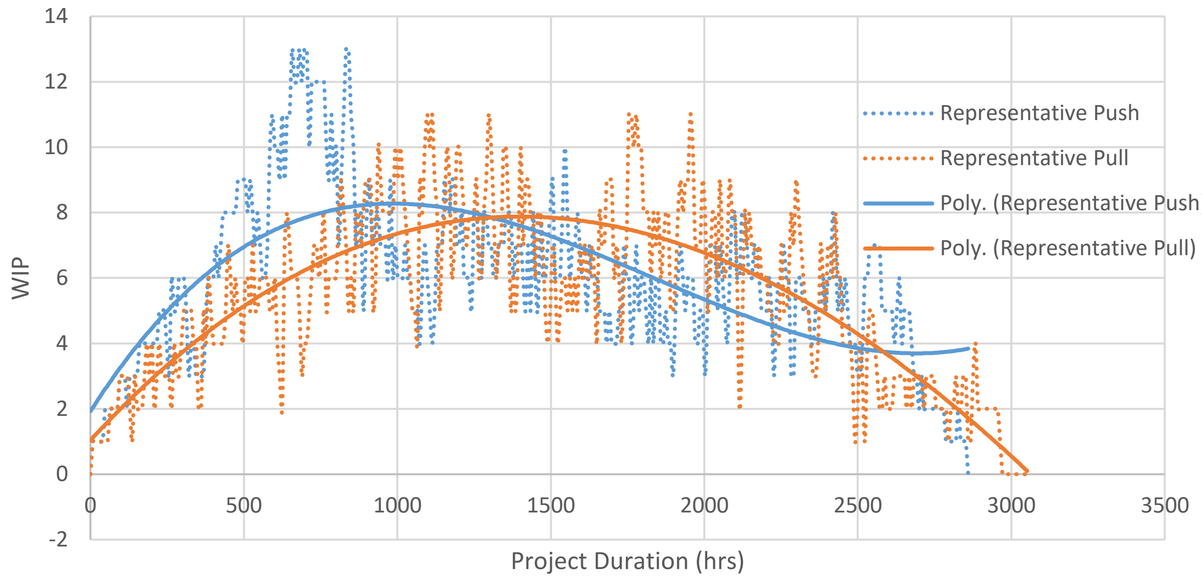

Figure 19 Variation of WIP for representative push and pull runs as a function of project duration

Figure 19 shows that pull scenario has a smooth trend line that start with low WIP, peaks throughout the middle of the project and then decreases gradually towards the end. The smooth parabolic trend is due the continuous lines of balance of activities. At first activities are only taking place in initial locations, then towards the middle of the project, there are tasks being executed in most of the project locations, and by the end of the project, most of locations that started first would be finished and tasks are mostly in last locations. This is a logical behavior for a takt plan. Whereas the push scenario witnessed fluctuating trend line of WIP, it increased sharply at the beginning of the project reaching a peak, which is higher than that reached in a pull scenario, then decreases forming a straight line before the project ends. This shows that even though the average standard deviation of WIP for push scenarios was less than that in pull cases, push scenarios have more unexpected variability than pull cases.

Besides, a representative push scenario is compared to a two pull scenarios, one having highest combination of WIP and its standard deviation and the other having the lowest. These graphs are shown in Figures 20 and 21 respectively.

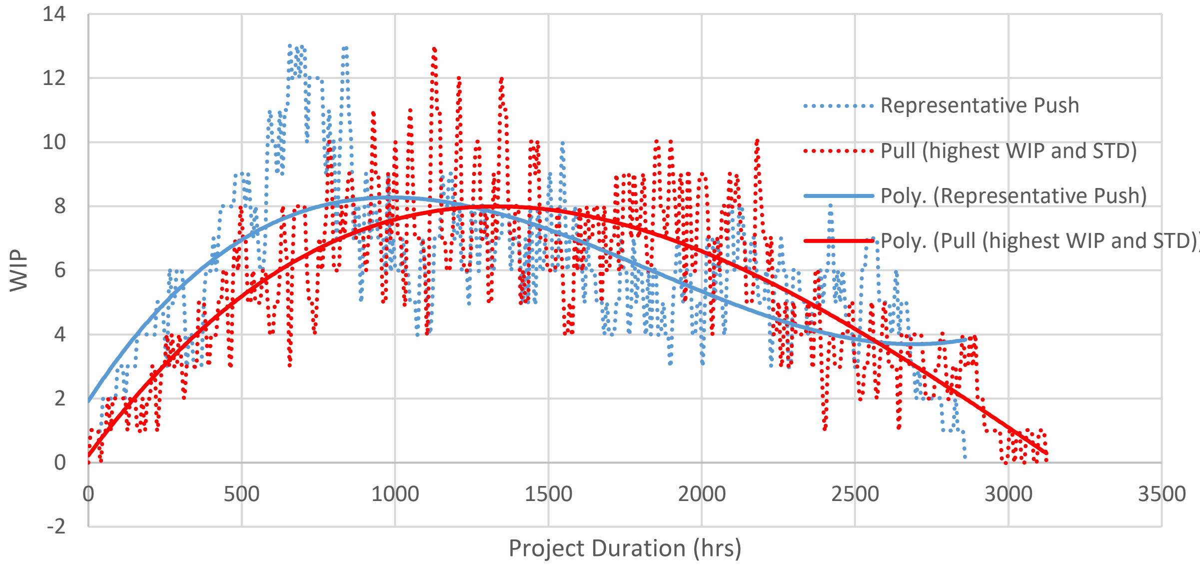

Figure 20 Variation of WIP for a representative push run and highest extreme pull run as a function of project duration

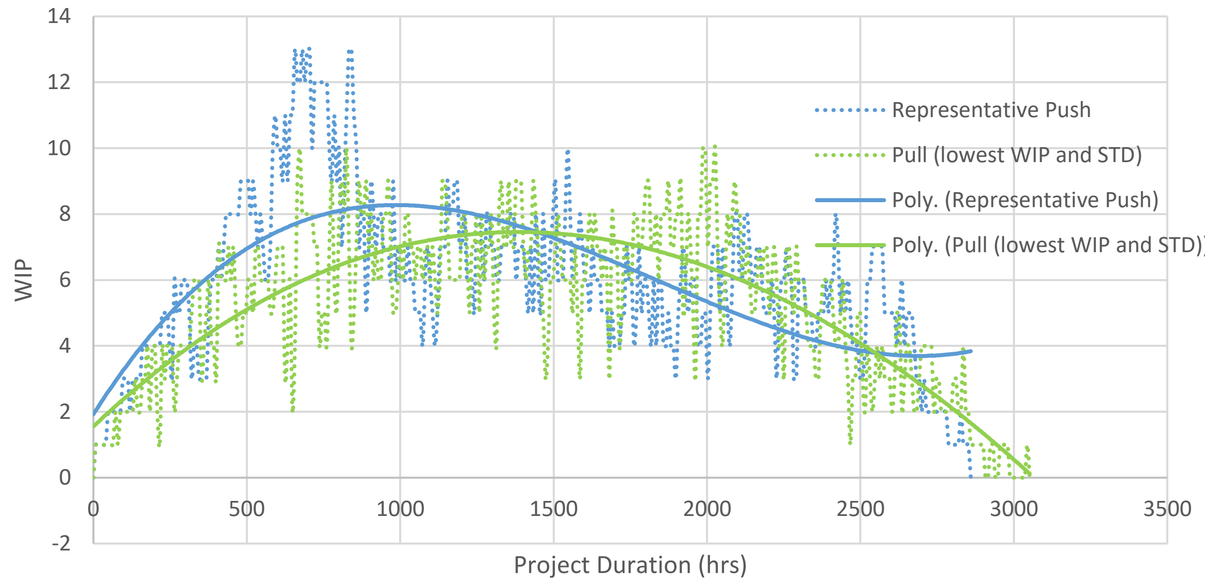

Figure 21 Variation of WIP for a representative push run and lowest extreme pull run as a function of project duration

It could be noticed from Figures 20 and 21 that pull scenarios having highest and lowest combination of WIP and its standard deviation (STD) had the same behavior as the representative case (showing the average), yet with different scale. This shows the consistency of pull techniques and the expected behavior of WIP accompanied with these techniques.

h. <u>Task Throughput:</u>

Task throughput measures the number of completed tasks through each working day. Representative simulation runs having a daily average (of tasks completed and standard deviation) very close to the average of all the simulation runs together are presented in Figure 22 below.

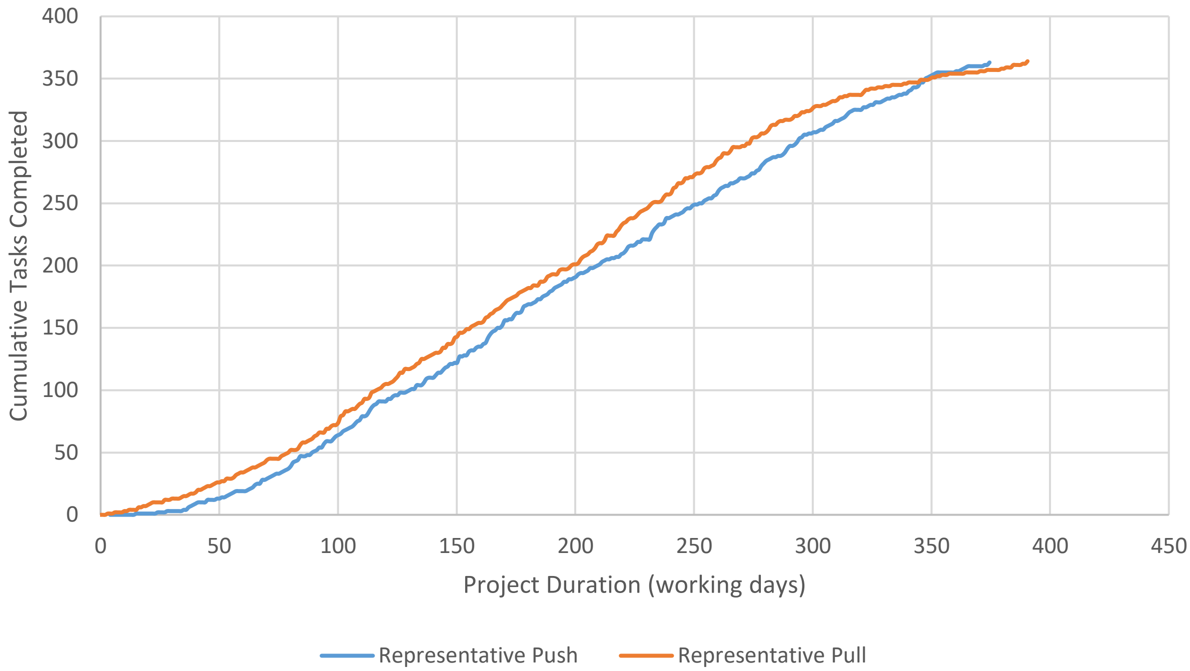

Figure 22 Variation of Task Throughput for representative push and pull runs as a function of project duration

It could be noticed from the graph shown in Figure 22 that pull and push scenarios did not show a clear difference regarding task throughput. Both curves started at a mild slope that sharpens throughout the middle of project, before getting back to a milder slope by the end of the project.

However, data collected from all simulations runs show that the whole pull dataset had a slightly slower pace at which tasks are being completed than that in push (lower task throughput average value). This could be related to the total project duration, whereby a slower pace in pull led to a slightly longer project duration for project completion.

i. <u>Task Instances:</u>

Task instances show how many interruptions each task has witnessed. It can be noticed that tasks were much less interrupted in pull scenarios than in push ones. This difference is mainly caused by the different methods used to handle late tasks in push and pull scenarios. In a push scenario, if a task becomes late, its utility increases making other crews leave "on time" or "early" tasks and move to this late task. There limit for crews working together is relatively high (75% of maximum resources in case of "late" task, and maximum resources except one crew in case of a task having "end date exceeded"). Thus, all crews working on an activity that is not late may leave their current task and move to the late one, which leads to task interruption. Then if the task becomes back on time, additional crews will leave the task and go back to other tasks having higher utilities.

Whereas in a pull scenario, the limit to crews working together is relatively less than that in push, and thus the probability of having all crews leave a task being executed to work in another one is much less. Imposing a limit to crews working together in a location together favors in an indirect way a basic concept of pull theory, which is ensuring activity continuity and not having an activity that is being executed to stop completely.

In addition, the difference in task instances is related to the turnover rate. High turnover shows a high probability of crews moving from an unfinished task to another. Results of turnover show a logical interpretation to task instances results, whereby both metrics had the same behavior in each of the push and pull conditions (high turnover and task instances in push cases, and relatively lower values for pull scenarios).

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Construction logistics and production control are essential systems that should be well maintained to preserve a successful project. Many studies have addressed techniques that improve logistics and production control. Besides, push planning and pull planning were compared from schedule and control perspective, paying less attention to the effect of these techniques on crew productivity and logistics at the level of project locations.

This study targets the implementation of these techniques (push and pull production control methods) at the level of project locations, and their effect on crews' and project performance metrics. This was accomplished by following a systematic methodology, whereby a thorough literature review was conducted, then research gaps were highlighted and addressed through objectives and research questions. After that, a conceptual model was created which depicts push and pull production control techniques at the level of locations and their effect on crew's interactions and logistics between locations. Then, AnyLogic was used to develop an agent-based model that represents a construction site, whereby crews work and interact with each other. During simulation, several metrics that give indications to crews and project performance were measured. These metrics were then compared in both push and pull scenarios, and results were analyzed accordingly.

The results obtained show that pull techniques have better results on most of the measured metrics. At the level of crews, pull scenarios resulted in higher productivity, lower idle time and turnover rate. These results show that pull techniques adopted in production control can enhance the overall performance of crews, which reduces additional cost and time delays associated with crews' low productivity and wasted idle time.

Moving to the results of push and pull techniques at the level of activities, it was noticed that in pull scenarios, tasks in general started later and finished earlier than tasks in push scenarios, showing that starting as soon as possible does not mean finishing earlier. Besides, tasks had less work interruptions and lower variability of work-in-progress (WIP) in pull scenarios. This ensures a continuous workflow of activities, with less fluctuation in the number of tasks that are being executed throughout the project duration.

Regarding metrics related to the project performance, it was noticed that push scenarios led to finishing the project in a shorter duration than pull scenarios. However, it required higher man-hours.

Summing up all metrics results, it can be concluded that both push and pull production control techniques have pros and cons, and adopting one of them to control the whole project would not lead to optimum results. Push and pull scenarios complement each other at some instance. A combination of these techniques could be used throughout the project to mitigate certain issues depending on each situation; controlling a project that is behind schedule may require some push techniques, maybe to some critical tasks only, whereas a project that is over budget could be handled through pull techniques. In complex projects, push and pull techniques could be applied together to reach a representative and flexible production control system.

Finally, some limitations to this study are worth to be mentioned and addressed in future research. Regarding the input of the agent-based model used, it could be further validated through assessing it in reference to different types of construction projects. Besides, considering construction logistics, the model considers continuous supply of material to all locations. Thus, future research can take into consideration the effect of applying push and just-in-time delivery approach for on-site materials along with push and pull production control systems.

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