

# SPACE SCHEDULING USING FLOW ANALYSIS

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## ABSTRACT

WorkMovePlan combines the Last Planner methodology, implemented in the WorkPlan software, with space scheduling. This allows the Last Planner to not only specify labor and equipment but also space as an explicit resource. WorkPlan guides the user step by step to plan work for the week ahead through the process of spelling out work packages, identifying constraints, checking constraint satisfaction, releasing work packages, and allocating labor and equipment; then at the end of the week, collecting field progress data and reasons for plan failure. WorkMovePlan extends these capabilities by allowing a user to specify site space needs on a day-to-day basis for labor, equipment, and materials in terms of work-, laydown-, or staging area as needed throughout the execution of a work package. WorkMovePlan also makes it possible for the user to designate the flow path that will be followed during movement. This user data then serves as input to simulate traffic on site. Output of the simulation helps the user assess the feasibility and desirability of traffic flow paths and thereby gauge the quality of a work sequence. This systematic approach helps the user create quality work plans and learn from understanding reasons for failure. The functionality of WorkMovePlan is detailed in this paper.

## KEYWORDS

Last Planner, WorkMovePlan, WorkPlan, weekly work plan, database, lean construction, work package, constraint, layout planning, space scheduling, materials management, simulation, flow.

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## INTRODUCTION

The traditional view of construction has been that it comprises a sequence of activities, essentially representing conversion processes. By contrast, the lean production view is to consider the flow as well as conversion processes in combination making up a system (Koskela 1992). A process consists of activities (such as ‘placing formwork’ and ‘moving pallets by forklift’) and buffers between activities. Buffers hold resources (such as an idle backhoe or materials waiting to be loaded) before they are engaged in an activity. Their presence or absence reflects the ability of resources to flow.

Activities can be value adding or non-value adding. Koskela categorized transportation as a non-value activity and proposed that it be minimized. This view generally holds though needs to be qualified. Indeed, since by definition value is created only when the product meets or exceeds the customer’s expectation<sup>3</sup>, most transportation does not create value and is thus waste. For example, a window frame waiting to be shipped from a fabrication shop is no different from a window frame ready to be installed but waiting in an on-site staging area. In both instances, the window is in a holding position. It has not yet been installed and is therefore not ready to be used and of no value to the customer. Nevertheless, windows need to be transported from the shop where they are made to a site staging area prior to being installed. While most of this transportation effort may be non-value adding to the customer, transportation to site and on site is a necessary part of the materials flow process and as such value adding. One could try to avoid having windows wait for transportation in the shop and for installation in the staging area. However, the practicality and cost-effectiveness of packaging and loading multiple units on a truck and handling them by crane or forklift is such that the handling batch size will be larger than one, thereby causing buffers and wait times, and thus hampering flow.

Examples abound where transportation is a value adding activity because it is a necessary if not essential part of a construction method or a production system. For instance, trucks may be positioned and pipe offloaded one piece at a time, so pipe can be staged along a trench and thereby allow for efficient placement later. A steel beam may be transported to a fabrication shop instead of being brought directly to site because it is more cost effective to fabricate it off-site even though the total transportation effort might be larger. Transportation is a very important part of any flow process and should be studied with the corresponding attention. It should include off-site as well as on-site resources, namely material, equipment, labor, as well as information.

## MODELING LAYOUT AND FLOW

Many layout and flow models have been developed to study manufacturing operations (e.g., Francis et al. 1992 for a description of various models). They usually assume a steady state operation of the facility. Manufacturing equipment tends to be stationary and the materials (or product) flow through it. The materials flow path tends to be predefined though it can vary from material to material or product to product. Labor typically supports a single machine or inspects one or several machines’ output for quality, so their movement on the job floor is rather limited. This situation leaves little room for variation in terms of space use.

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<sup>3</sup> At least, this is one definition of ‘value’ and it certainly is open for discussion.

The speed of travel through the job floor is determined by the transportation equipment used (such as a conveyor belt, a robot, or an automated guided vehicle). It may vary probabilistically but it too is relatively well defined. Existing layout models for manufacturing therefore rely on a deterministic number of trips traveled between the (usually center points of) layout components and the static attract/repel preference. The animation of results from simulation (e.g., Law and Kelton 1991) often relies on static layouts for input (e.g., Proof 1995) though flows can be probabilistic. The resulting data provides the basis for generating layout solutions that presumably will remain effective for a relatively long time.

Construction layouts are much more dynamic. Every day a site may be laid out differently, because work areas move around and crews and materials come and go based on the start and finish, and throughout the execution of an activity. We therefore set out to develop a scheduling tool that could represent the short term, dynamic characteristics of site space use. To account for variability in flow speed and paths, this tool has been integrated with simulation capabilities to provide quantitative output, namely a numeric score (a user-defined, heuristic combination of travel time, travel distance, number of path intersections, and wait time) for the layout that enables the user to compare this layout with others.

## RELATED WORK

Inadequate work space and interference during travel can result in access blockage, congestion, safety hazards, and risk of damaging the end product (Oglesby et al. 1989, Tommelein 1991, Thabet 1992, Tommelein et al. 1992, 1993, Riley and Sanvido 1995, Akinci et al. 1998) thereby creating waste in the workflow and diminishing productivity. Some examples of waste due to interference are needless wait of one work crew for another work crew to clear an area, rework created by having to do work out of sequence, and constructability problems. Our premise is that detailed scheduling of workspace before execution of work can prevent many of these kinds of waste.

“Space scheduling” is “the problem of allocating space to resources governed by a construction schedule, and conversely, changing the schedule when space availability is inadequate” (Tommelein and Zouein 1993). When one wants to capture the dynamic nature of a construction site layout, space scheduling must be done in small time intervals (e.g., days or weeks, as done by Zouein and Tommelein 1999) as the uncertainty increases dramatically for work to be done further out in the future. Accordingly, we are building on data available in weekly work plans, which is the most detailed level of scheduling in construction, to specify work and its associated space use.

The representation for planning labor and equipment assignment is straightforward and can be established by means of scalar variables that describe “WHO (or WHAT) is scheduled to be used WHEN for HOW LONG”. The description of space use is: “WHERE is WHAT scheduled to be used WHEN for HOW LONG”. However, there is a difference between WHO (or WHAT) and WHERE. The first (and second) can be described with a single identifier whereas the third requires more than one identifier. Spatial information is not easy to convey as a scalar variable. It is best done using a 2-D or a 3-D graphical representation combined with human judgement on what to abstract away. For example, WHERE may consist of a reference point describing the object’s location ( $X_1, Y_1, Z_1$ ) and the dimensions of that object in space ( $\Delta X, \Delta Y, \Delta Z$ ). In this paper, we present the WorkMovePlan database

system that includes a 2-D interface to keep track of the space need, timing, and location. Output from WorkMovePlan can be used to create 3-D virtual reality models.

### APPLICATION OF LEAN CONSTRUCTION TO SPACE SCHEDULING

Most existing layout planning tools focus on minimizing the travel distance or the cost of a static layout at a certain time or rely upon heuristics to reach a near-optimal solution (e.g., Tommelein et al. 1992, Yeh 1995, Cheng and O'Connor 1996). Not many consider flow, including intermediate putting down and picking up because of staging. Figure 1 depicts the desirability of flow between off- and on-site where the heavier arrows represent flow that is more desirable than the flow depicted by light arrows. Dashed lines indicate flow that should be avoided, provided all other things are equal. This drawing can guide a planner in optimizing a site layout but it does not guarantee selection of the best construction method or optimal schedule and cost for construction.

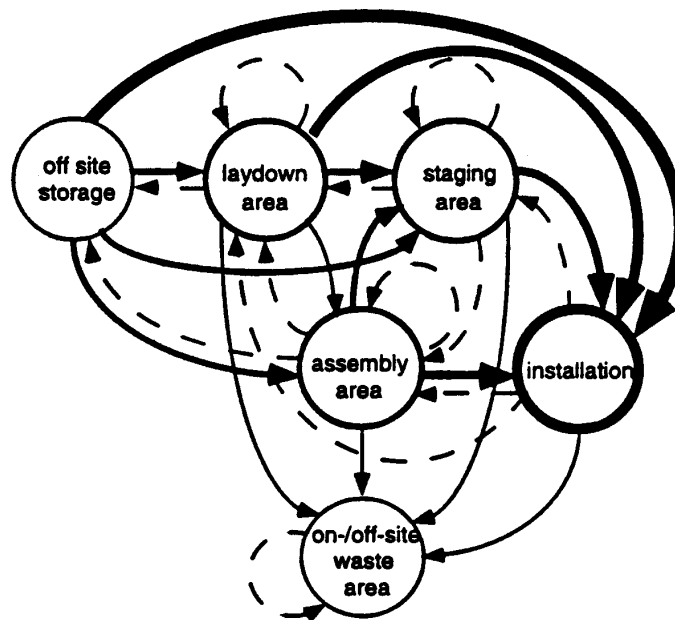


Figure 1: Preferred material flow (from Tommelein 1994)

In construction, means for handling many materials are often not predetermined because they will depend on actual site circumstances. For instance, sections of HVAC duct can be lifted by elevator when a crane is not available. In addition, resources rarely travel alone. Laborers or equipment carry materials or hold them in place during installation. They then return empty-handed to get more materials. Yet, most existing layout planning tools do not represent combinations of resources such as laborer-with-materials (simulation tools, however, do and they accordingly refer to ‘compound resources’). Neither do layout planning tools distinguish a haul path from a return path. Movement of materials between layout components are often weighed in terms of travel frequency and expressed by a 1-to-1 relationship. By contrast, we distinguish flow of single resources from flow of combined resources in order to better approximate reality and better characterize flows, especially those

that may cause interference. This distinction also weighs in when one trades off alternative means and methods (Odeh 1992).

To represent the role of each resource and layout component, we created a new symbol system. Our system builds upon the symbols used to describe manufacturing activities though we have made significant changes to represent flows of material, equipment, and labor on site. We also wanted to make the production system explicit (including information flows and means to maintain buffers) and study the impact of uncertainty on flow. Our system is layered to represent different problem features at different levels so as to keep each layer easy to interpret.

## **MODEL CHARACTERISTICS AND IMPLEMENTATION**

### **WORKMOVEPLAN**

WorkMovePlan integrates WorkPlan (Choo et al. 1999) with site layout scheduling. WorkPlan treated the space requirements for each work package as a constraint, where a constraint is represented by an item in a checklist that reads for instance “check for space requirement.” An open check box next to the item means the constraint remains to be satisfied, whereas a checkmark means it has been satisfied. By contrast, WorkMovePlan treats space as an explicit resource that can be assigned individually to any or all resources in a work package or group of work packages. Accordingly WorkMovePlan provides a new tool to the Last Planner (Ballard and Howell 1994) who is responsible for assigning not only labor and equipment but also space to accommodate the execution of a work package on site.

WorkMovePlan supports the space scheduling task. Figure 2 shows WorkMovePlan’s Space Scheduling Screen, used to specify space needs from the moment of delivery or unloading time to work package completion or cleanup. First a work package is selected (97-309-C-1000) and a resource (Loader) is then chosen that will occupy yet-to-be-determined space on site. ‘Shape’ refers to the physical shape of the space required. X, Y, and height (Z) refer to the dimensions of the space. A color can also be picked. Although the dimensions are listed in 3-D, space scheduling will be done using a 2-D layout.

The ‘Name’ list in the middle of the screen shows the schedule for labor and equipment assigned to the selected work package. The default time frame for space need is from the first to the last day of labor or equipment assignment. This time frame can be manually adjusted to represent the actual schedule if a material is to arrive before the start of the work package or to represent space taken up by debris and awaiting cleanup after completion of the work package.

The “Resources to be on site” list refers to all resources that have been input through the Space Scheduling Screen. These resources will share site space for the week under consideration. Although any type of space use can be specified in WorkMovePlan, the main focus is on the flow of material, labor, and equipment, so these are listed in the default categories. Other categories can be included, if needed.

Once all resources to be assigned are specified, their layout positions can be selected relative to a layout ‘backdrop’. Each construction project must have a ‘backdrop’ showing existing facilities (or walls etc. at their appropriate stage of completion) and site boundaries. This drawing can either be imported from another CAD program or drawn by the user. Its

main purpose is to provide users with a frame of reference to identify relative locations of space to be assigned.

### Space Scheduling

**Please specify all resources that require space on site**

Work Package No:  Categories:

Description:

Shape:  Rectangle  Circle  Triangle

X:  Y:  Height:  Color:

Name	28	1	2	3	4	5	6	7	8	9	10	11	12	13
Gray Andre			8	8										
Patterson Andy		8	8	8										
Air Compressor		8	8											

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**Resources to be on site**

Work Package No	Categories	Description	Shape
97-309-C-1000	Labor	Working Area	Triangle
97-309-C-1000	Material	Staging Area	Triangle
97-309-C-110	Labor	Working Area	Rectangle
97-309-C-400	Material	Dirt Pile	Circle
97-309-C-400	Material	Pallets	Rectangle
97-309-C-500	Material	Pallets of Cement	Circle

Figure 2: Space Scheduling Screen

WorkMovePlan’s layout interface was built using Visio ([www.visio.com](http://www.visio.com)) for ease of use and speed of the program. 2-D schematic layouts are quick to display and really all that is needed for most space scheduling situations (exceptions are, e.g., heavy crane lifts or other critical operations, see Bohinsky and Fails 1991, Lin and Haas 1996). Even overhead work typically requires ground access or prohibition of access by others for safety reasons. In today’s practice, most site layouts done on paper or using CAD are based on a grid system, where a number of selected grids form a site layout component allotting space to, e.g., a room, elevator, laydown yard, or staging area. This form of representation serves site managers well because pinpointing the exact space needs or locations for most site layout components is not worth the effort and is not easy to achieve anyway. Therefore, WorkMovePlan drawings are schematics (using simple geometric icons such as rectangles, triangles, and circles). 2-D

layouts convey the space scheduling information in a straightforward fashion. Nevertheless, the height dimension entered in WorkMovePlan can later be combined with the layout schematic to generate a 3-D virtual reality mock-up using the Virtual Reality Modeling Language (VRML 1995) for instance.

For each work package, work space can be assigned where all the material, equipment, and labor come together to result in work-in-place. This work-in-place can block out a part of the site layout to avoid space conflicts. Work space can be stationary (occupied from the start to the end of the work package) or progressive (starting at one position and moving to another). Since the minimum duration for a space layout is one day, it is implied that work space remains stationary throughout each day. Similarly, the user needs to specify space requirements for materials and equipment specifically and it is implied that these also remain stationary throughout the day. That is, WorkMovePlan generates a single layout for each day. Thanks to this rule the number of records in the database is kept relatively small. . A finer division of space use throughout the day would require extending WorkPlan as well as WorkMovePlan with a daily time schedule. At present, a resource can be active for only part of a day (as shown in Figure 2), but the user cannot specify which part.

Once the list of required space is specified in WorkMovePlan, the actual space assignment can begin. For all space needs that have been specified, WorkMovePlan automatically generates templates in the 2-D Visio environment for the user to drag and drop into a specific location.

Once all space needs are specified using this screen interface and located using a Visio drawing, the relationship between space uses can be specified so the planner can explicitly express the assumptions made when designating an area for a specific use. This way, the space plan is useful not only to a single contractor, but also to all others involved with site work as they can anticipate movement of labor or equipment in specific area. For a detailed analysis of flow, the resulting space layout serves as the basis for developing a discrete-event simulation model.

## **EXAMPLE APPLICATION: CONSTRUCTION OF A RAISED HIGHWAY**

### **PROJECT DESCRIPTION**

Consider the site layout of a project that consists of building a raised, curved highway made of reinforced concrete box girders. Figure 3 shows the highway divided up in sections of approximately 50 m long as defined by the length of post-tensioning cables. The lower part of the box girders has already been placed and the work now consists of forming and placing the ribs. Three long forms, each one of about 15 m, and a small one of about 5 m span the length of each section. 12 such sets (1 on each exterior side and 5 pairs of 2 at the inside) are needed to cover the width of this 4-lane highway.

We observed placement of those formwork panels. Panels are taken from the area where clean forms are stored. A crane lifts one panel at a time to height and holds it in place while a crew tightens it down with bolts. The crane also hoists a bucket of bolts to supply the crew when more are needed. After placing reinforcing bars, then placing concrete and allowing it to cure, the crane helps strip the panels and swings them to the used formwork area, where forms are cleaned and made ready for reuse.

The cleaning crew can move panels by hand over a short distance. However, a forklift moves cleaned panels to the area for pickup by the crane. This double movement of cleaned forms is necessary because construction work progresses and the crane must be relocated accordingly. The work area for cleaning forms thus gets out of crane reach and the crane is a constraining resource for formwork placement.

**SITE LAYOUT MODEL**

Figure 3 depicts the actual geometry of the site and its layout components, what we term the ‘site layout model.’ Construction of the raised highway progresses from the right side of Figure 3 to the left. Forms are being placed in section II. Concrete already has set and cured in section I, so forms there are ready to be stripped. When work later moves to section III, the formwork cleaning and staging areas as well as the crane will move along in the same direction.

The site layout model does not represent the relationships between the different components and how they will get moved in the course of a construction operation. In order to represent this additional information, we superimpose two layers on this model, what we term the ‘physical flow model’ and the ‘process flow model.’

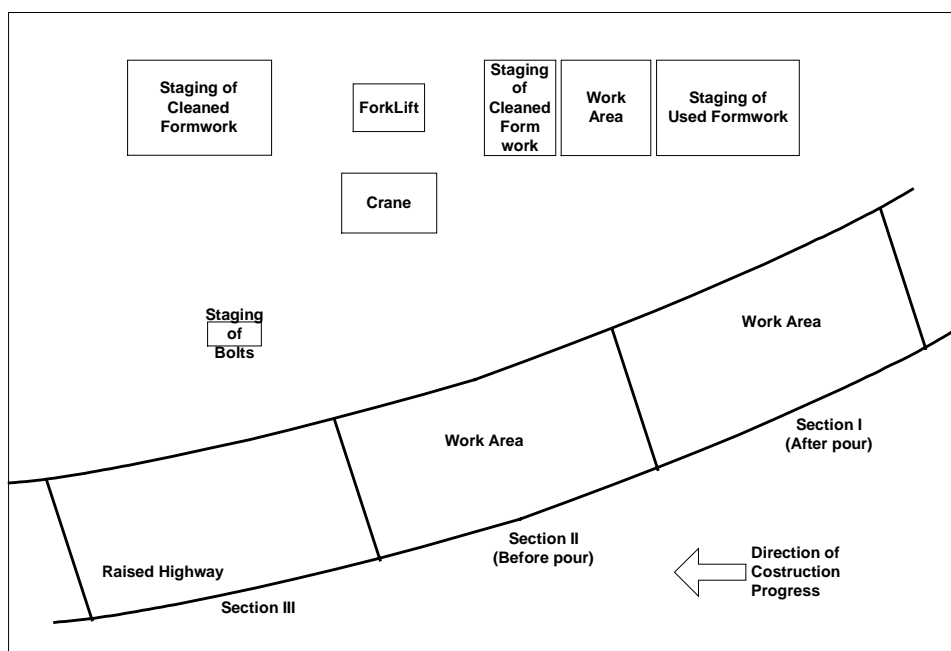


Figure 3: Site Layout Model

**PHYSICAL FLOW MODEL**

The physical flow model depicts the trajectory followed by materials, equipment, and laborers moving about the site. It also distinguishes what the various areas are used for.

Table 1 describes all symbols used in this model. Occupied space is abstracted to geometric symbols, including rectangles and circles. In addition, materials can be stacked horizontally (e.g., drywall) or vertically (e.g., windows leaning against a wall), or be



palletized. ‘A’ denotes a work area, ‘M’ materials staging, ‘E’ equipment, and ‘n’ the number of people on a crew working in an area. Arrows indicate flow. They emanate from the center point of one area and point to the center point of another area. Solid-line arrows denote movement with materials and dashed lines movement of equipment or laborers alone. A jagged line denotes information flow.

A key issue in flow modeling and especially when it comes to acknowledging uncertainties is “Where *exactly* are equipment, materials, and laborers relative to the area they are located or working in?” Two alternatives are possible in our model. Resources are all assumed to be (1) concentrated at the center point of the area or (2) uniformly distributed over the area. Spread-out materials, equipment, laborers and the distribution of work relative to an area can thus be modeled.

The uniform distribution is sampled from during simulation in order to reflect uncertainty in terms of spatial distribution. Sampling will be more appropriate than choosing the center point (or some other representative point in an area) when variability of distances is critical to understanding flow bottlenecks (Tommelein 1999). Most existing layout programs do not model such variability. They rely on the center point assumption and are therefore unable to identify congestion and bunching effects.

Category	Meaning	Layout Symbols	Production Symbols
Area	Operation with rectangular work area		
	Operation with circular work area		
Labor	Labor with work space (n = crew size)		
Material	Storage with rectangular footprint		
	Storage with circular footprint		
	Horizontal stack		
	Vertical stack		
	Pallet		
Equipment	Equipment with rectangular footprint		
	Equipment with circular footprint		
Flow	Movement of equipment with material		
	Movement of equipment without material		
	Movement of laborers with material		
	Movement of laborers without material		
	Information flow		

Table 1: Symbols depicting on-site activities, resources, and flow

Figure 4 shows the physical flow model. For the time being (as our model is still being developed), all flow paths are assumed to follow straight lines. Arrows indicate materials

being moved by crane and by forklift. Note that most solid arrows, which indicate movement of equipment with materials or labor with materials, are complemented by dashed arrows, which indicate movement of the equipment alone or labor alone. However, some additional movement is needed for equipment to get from one drop-off point to a new pick-up point.

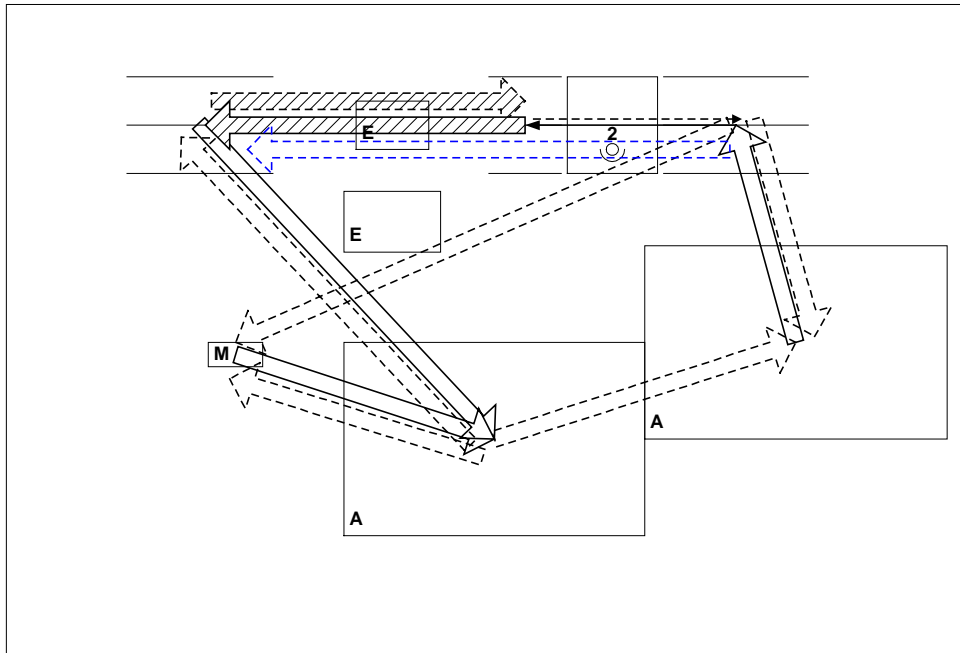


Figure 4: Physical Flow Model

### PROCESS FLOW MODEL

The process flow model (Figure 5) depicts the actual steps that will be taken in the course of a process. In many ways, features shown at this level are akin to the process charts that were developed for discrete-event simulation (e.g., Halpin and Riggs 1992). However, we distinguish communication of information from materials flow as is also done in the process maps presented by Rother and Shook (1998). The reason for doing so is that we want to show what controls the sequencing of operations, that is, what directives are driving process execution, including buffer depletion and replenishment. No directives or information flow are visible in the site layout model or in the physical flow model.

As for the situation depicted here, work is driven by the contents of inventories on site. When workers installing forms have few bolts remaining to do their work, they need the crane to hoist up another bucket. Bolts are thus replenished as if they were managed by a ‘supermarket’ system (depicted by  $\Xi$ , see Rother and Shook 1998) that has minimum and maximum inventory levels. However, bolts are brought to site in bulk and stored at ground level in an unrestricted buffer (depicted by  $\Delta$ , see Rother and Shook 1998). In this example, all other materials on site are stored in similar, unrestricted buffers.

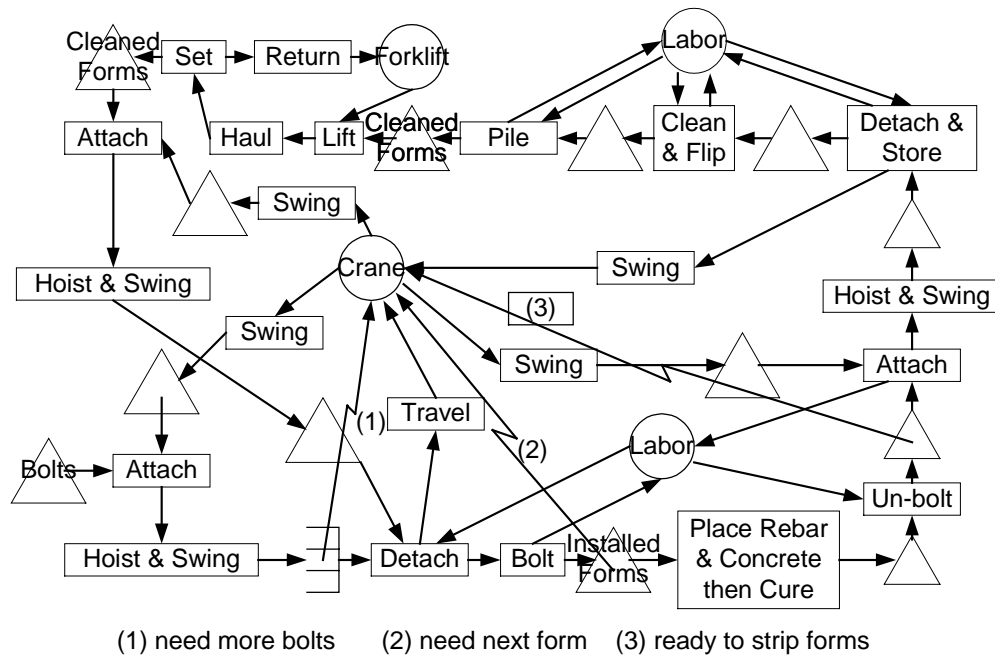


Figure 5: Process Flow Model

**FUTURE DEVELOPMENTS AND FIELD TESTING**

The example given in this paper demonstrated the use of the WorkMovePlan tool under development. No simulation model results assessing the quality of the layout, nor results from field testing can be reported at this time. Although most of the capabilities have been implemented, some additions and modifications still remain to be made. Testing will then help determine the usefulness of the tool.

**SUMMARY**

This paper presented the WorkMovePlan system that supports the Last Planner in checking the quality of assignments not only in terms of scalar constraint satisfaction but also in terms of their space requirements. WorkMovePlan is a three-tiered model, allowing users to specify the site layout, the physical flow, as well as the process flow. The three layers are integrated with one another so that layout data (e.g., distances) can be used in process simulation. Depiction of the physical flow helps a user locate possible bottlenecks and interference problems. Path crossings can also be captured in the simulation model. The linkage between the layout (CAD, generally speaking), the physical model, the process model, and the simulation it supports provide output that is key to quantifying the quality of one layout alternative over another (also see Odeh 1992, Abourizk and Mather 1998).

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