UNDERSTANDING FLOW AND MICRO-VARIABILITY IN CONSTRUCTION: THEORY AND PRACTICE

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Abstract

Uncertainty within supply chains, design changes, and lack of predictability of the production capacity of subcontracting trades, are only a few of the factors that make construction projects unpredictable. For residential finishing works, this is true even at the daily level; however most available production control methods, such as Last Planner, do not operate at this resolution. As a result, a production system is needed in which intelligent decisions about effective utilisation of available resources can be made daily or even hourly. A theoretical understanding is needed of the flow of operations on the micro-level of project management – at the level of daily resource utilisation – in order to develop appropriate systems. Various models of process flow developed in manufacturing industries for management of production on the operational level, which might apply to construction, are presented and discussed. A detailed case study, in which the patterns of flow of finishing trades were observed and recorded in a large residential project, provided a basis for exploration of different models. The patterns of flow of trade crews through the building demonstrate re-entrant flow similar to that found in semiconductor job shop situations, but also exhibit differences and contradictions with the main assumptions of factory production management. Heuristic solutions appear to hold promise for guiding the flow of construction crews at the daily operational level if and when conditions emerge that invalidate work packages assigned in a weekly work plan.

KEY WORDS

Micro-variability, production flow, project management, resource utilisation, trade flow.

INTRODUCTION

Construction projects are characterized by highly variable production rates. The effect of variability on construction cycle times can be considered on different project levels, from *micro-variability* on the level of individual resource utilisation up to *macro-variability* of overall cycle time. Insufficient management of micro-variability induces fluctuation at higher levels, thereby making projects less stable and predictable, and introducing waste. The detrimental impact of variability is clearly demonstrated in the Parade of Trades simulation (Tommelein et al. 1999). It is also clearly revealed in field studies (Thomas et al. 2002; Sacks and Goldin 2007). We assume that managing micro-variability at the level of daily resource utilisation can help improve project stability at macro levels, and that micro-variability can be managed through implementation of lean principles to daily resource allocations, principally by using pull flow signals.

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However, designing production systems capable of absorbing or reducing variability presupposes an understanding of the factors that may disturb continuous workflow. A theoretical understanding is needed of micro-variability so that it can be considered in work planning and/or action can be taken to overcome it. A major obstacle for accurate and reliable prediction of workflow progress at the micro-management level is that the existing theoretical foundation for construction project management, and the practical tools based on it (such as the critical path method (CPM) and software), do not consider varying production rates within activities, splitting, interdependence, and interactions between activities, movement of resources between activities, and do not account for uncertainty. Process flow theories for manufacturing, such as semiconductor production, provide some insights, but differ in important ways from construction production flows.

This paper presents and discusses various models of process flow that might apply to construction. It then presents a case study in which various finishing works were observed and recorded in detail in a large residential project (comprising two towers with some 280 apartments). Not only do the results highlight the presence of variation in production rates, but patterns of flow behaviour that cannot be classified as either pull or push were observed. These factors, and their undermining role for overall project progress, are described and discussed.

CONSTRUCTION MANAGEMENT APPROACHES

Construction is predominantly managed according to the transformation concept (Koskela and Vrijhoef 2000). The main principle in the transformation model is that the total transformation can be achieved only by realizing all parts of it. Thus, the total transformation is decomposed into parts and further into *tasks*, which are then assigned to operatives or workstations.

The central idea of production as a flow is to introduce time as a resource of production (Koskela and Vrijhoef 2000; Womack and Jones 2003). Two types of activities consume time when viewed from the product point of view: value-adding activities and others, apparently non-value-adding activities. The classification of activities may vary, but the main conceptual result of this theory is that it defines elimination of waste in process, i.e. non-value-adding activities, as a goal.

Koskela (1999) draws an analogy between car production and construction process to illustrate construction production flow. Car production has two material flows: the main flow of the car body through the assembly line and the flow of components to the assembly line. Production in construction is also of assembly-type, but in construction, there are three flows. The material flow of components to the site is comparable to that of car production. The building frame proceeds through the different assembly phases (referring to processing of all locations by a workstation), like a car proceeds through different workstations. However, due to the size of a construction product, there is an additional workflow where all installation locations proceed through the workstations, called ‘*location flow*’ (Koskela 1999). However, a building is immobile, contrary to a car body; and construction trades are not stationary, contrary to factory workstations.

A construction ‘assembly line’ consists of operations involving a high number of input flows. Resources (components and materials, labour, equipment, information, auxiliary tools) flow through different locations on site. The flows may combine, split, and recombine thereby producing trade workflow. Any construction activity can be performed only when all required input flows with minimal required volumes appear simultaneously in a given location.

Similarly to a factory assembly line, slowing down of productivity of only a single trade leads to accumulation of work resources in front of a particular location. The slow process becomes the weakest link of the project chain – the flow bottleneck - which disturbs the subsequent trades' flows. Acceleration of production of only a single trade leads to accumulation of work locations in front of the successive trades. Usually, to ensure continuous workflow of the fast trade and maintain its' high productivity, managers push new locations into production, thereby building up work-in-process (WIP) and production cycle times (CT).

The Last Planner System™ (LPS), which relates directly to flow stability and reliability, is a well developed lean-production tool for project planning and management (Ballard 2000). Implementation of the LPS demonstrates continuous improvement of project flow and increased levels of PPC. However, even where the LPS has been applied well, PPC levels of 100% have not been achieved (Bortolazza et al. 2005). The techniques that have been developed extend from project master plans through look-ahead plans and to weekly work plans, but do not extend to real-time assistance, and thus are not capable of reacting to unpredicted conditions emerging through a working day. The LPS has no mechanism to prioritize the work packages already filtered through a make-ready process; such a mechanism could provide guidance as to which alternate ready work packages are to be preferred if and when previously selected packages become impractical.

JOB SHOP SCHEDULING

The problem of effective daily resource utilisation (i.e. assigning varied tasks to work resources) can be compared to the *job shop scheduling problem* in manufacturing. In general, the job shop scheduling problem is one in which *n* jobs must be processed through *m* machines. In real job shops, not all jobs are assumed to require exactly *m* operations, and some jobs may require multiple operations on a single machine (Nahmias 1997; Askin and Goldberg 2002). In general, the job shop scheduling problem may be formulated as the need to find the optimal job sequences and batch sizes on each particular machine (or workstation) according to chosen optimization criteria. Some of the most common scheduling optimization problems are: 1) meet due dates, 2) minimize the average flow time or jobs makespan, 3) minimize work-in-process (WIP) inventory, or 4) provide high machine/worker time utilisation (minimize idle times). Due to the NP-hardness[3] of the general scheduling problem, an entire production system is usually decomposed into smaller production centres or single work stations, which are scheduled individually.

According to the Theory of Constraints (Goldratt 1990), overall manufacturing system throughput is strongly dependent on bottleneck scheduling and the bottleneck production rate. Goldratt (1997) proposed the drum-buffer-rope scheduling technique for entire job shop scheduling. The critical chain is defined as the set of tasks that determines the overall duration of the project, taking into account both resource and precedence dependencies. Then the bottleneck facility should be identified and scheduled. Next, based on this schedule, non-bottleneck facilities are scheduled in backward and forward manner, fitting the bottleneck capacity.

Construction production processes have a *'floating'* bottleneck. At any stage of project progress, any trade that slows down its production rate or lingers at any

[3] NP-hard problems are problems for which there is no known polynomial algorithm, so that the time to find a solution grows exponentially (i.e. much more rapidly than a polynomial function) in problem size.

location may become a flow bottleneck. Therefore, under the bottleneck scheduling approach, effective stabilization of construction flow depends on the ability of the works manager to identify or predict which activity is the bottleneck process at any time, and schedule or manage it properly in order to ensure it continuous workflow.

Re-entrance is another peculiarity of construction production flow. In manufacturing, re-entrance is the phenomenon where a product must pass through a production step multiple times. Re-entrant flow patterns are typical for the semiconductor manufacturing process, where multilayer semiconductor wafers return several times to the same workstation for creation of successive layers (Vargas-Villamil and Rivera 1997). In construction, trade teams are required to work in the same locations multiple times, such as when a drywall crew first erects framing, then returns later for the first side of gypsum boards, and later again to close the second side and apply finishes. Implementation of TOC-based shop floor control for re-entrant processes poses a number of challenges, because each product often visits the bottleneck several times before completion.

A large number of publications have been devoted to semiconductor job shop scheduling; almost all decision methods were employed, and different solutions were proposed (Blazewicz et al. 1996; Gupta and Sivakumar 2004). A survey of these solutions shows that heuristic rules have strong advantages in that they are easy to understand, easy to apply, and require relatively little computer time. They are procedures designed to provide good solutions to complex problems in real-time.

CASE STUDY

A large residential project with two towers (35 and 40 stories) and some 280 apartments was studied over a period of six months. The round towers have cast in place concrete cores and structural frames, enveloped with curtain walls of aluminium and glass. Construction began in August 2005, the structure of the first tower was completed in August 2006 and the second will be completed in May 2007. Finishing works in apartments of the first tower started in January 2006. By April 2007 about 93 apartments were in process, while the finishing works in the second tower had not yet commenced.

The main finishing works in the apartments are: concrete block division walls; marking; sewage and drainage pipes; concrete base beams for internal partitions; drywall partitions; HVAC ducts; electrical, plumbing, sprinkler and other systems in walls and ceilings; false ceilings; and floor tiling. Over 60 trade subcontractors were employed in the finishing works at different stages.

The study comprised observation and monitoring of the main finishing works within apartments. Trades' productivity was measured through performance of several repetitive apartments. The primary purpose of the study was to understand the main features and patterns of ***flow*** of the work, the apartment 'products' and the trade teams.

Almost all activities defined in the master plan comprise several stages. These stages may be performed continuously by a single trade, or may require interchange with other stages performed by other trades. For example, building of drywalls, which includes a) stud framework, b) coverage of one side with gypsum boards, and c) closure of the second side with boards, is interrupted for installation of systems within the wall cavity.

Many finishing activities do not have tight technological precedence constraints. For example, installation of air conditioning fibreglass ducts should begin after drywalls are built and the openings for ducts are prepared. The CPM schedule for the project models these tasks using finish–start or start-start links with delays. However, installation of a duct requires that a specific wall section be built. Thus, installation of ducts may be able to start even when only a single section of wall is built; on the other hand, a situation may arise where 95 % of the walls have been built, but a particular wall section is not in place, and so duct installation can not start. Existing planning and control tools do not enable monitoring of finishing activities at such a detailed level. As a result, finishing activities were combined in sets, and the desirable production period was determined for each set of activities by collecting them in a summary task, as shown in Figure 5.

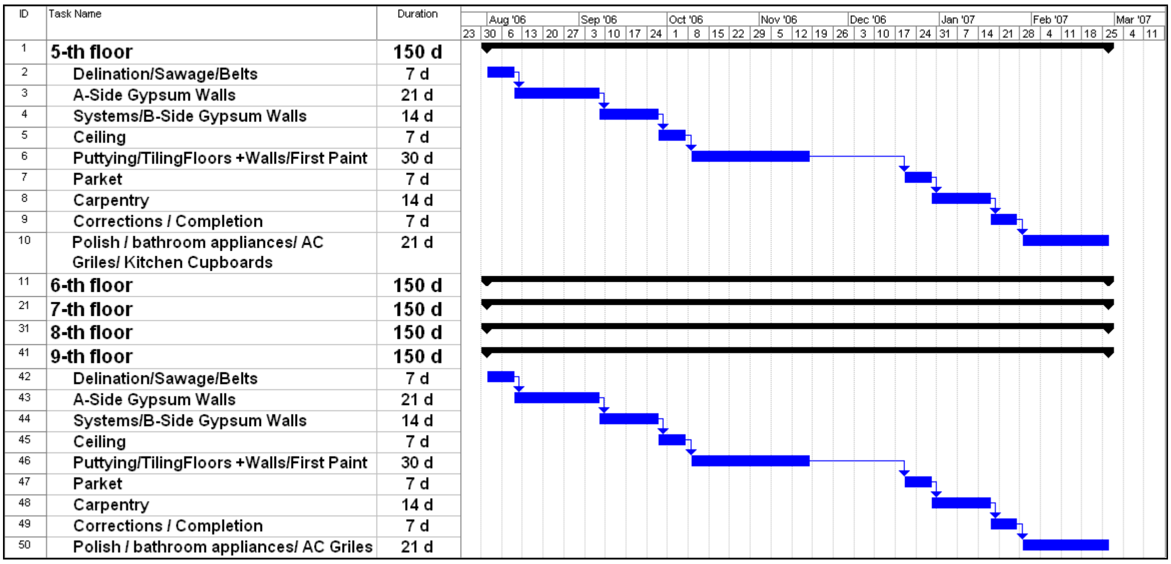

Figure 5: Sample of the project schedule prepared by the construction management team.

With centralized control using CPM type tools, short term planning requires accurate determination of the duration of remaining activities (or sub-activities). The CPM approach assumes prognosis of workflow progress according to the Earned Value Method (Hendrickson 2003). The method is based on the assumption that production rates are constant throughout execution of each work package. We assume a priori, that contrary to this assumption, that actual production rates within activities are not constant.

PRODUCT FLOW

Detailed performance data were collected for two trades: floor tiling and installation of prefabricated fibreglass air conditioning ducts. Each trade's production was measured every 5 work minutes through execution of numerous whole apartment work packages. In both cases all the prerequisites - materials, information, auxiliary tools, etc. - were reported satisfied at the beginning of work in each apartment.

As expected, the curves show that production rates varied within each work package and that production rates varied even when all the prerequisites were fulfilled. We call this '*inherent variability*'. For example, Figure 6 represents the production curve for tiling an entire apartment with six distinct spaces. Each horizontal section of the cumulative production curve, where the production rate falls to zero, indicates beginning of tiling in the next space. Tiling of each new work space starts from marking up. Then, value is accumulated at an almost constant rate as tiles are laid. Production slows down in more complicated zones where tiles must be cut to fit. The complexity of the work can be defined as the ratio of the number of tiles that must be cut and adjusted to the overall number of tiles that must be placed. Also, if tiling within any space is interrupted, marking of the space must be redone.

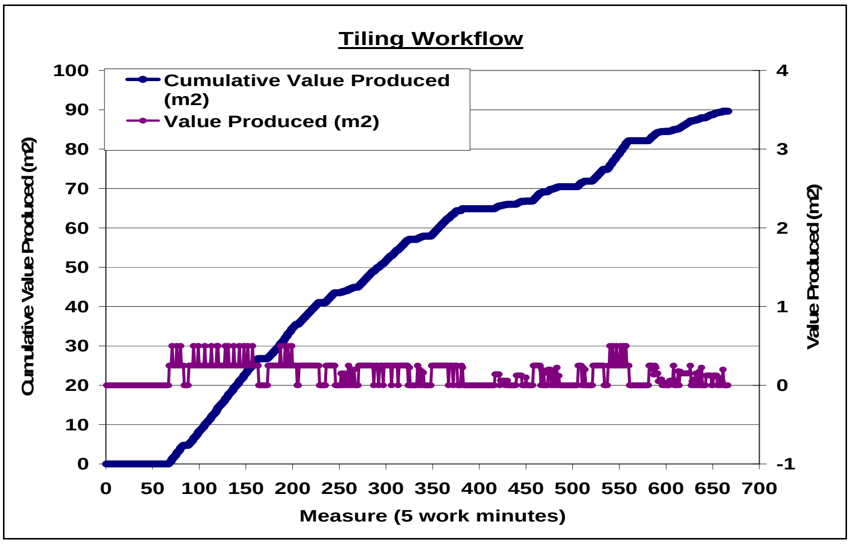

Figure 6: Workflow of tiling trade through single apartment

The second example is installation of prefabricated fibreglass ducts for an air conditioning system (Figure 7). Installation usually begins from open spaces, where large size parts may be installed and connected. Finally, all the branches, distributed within rooms, are connected. Due to the multitude of branches and the presence of other systems, the work in these areas is more complicated and requires more time for installation and adjustment, but the parts installed are relatively small. Each step on the production curve is equal to a length of duct part installed. The production rate slows down toward the end of the activity. The rate reduction may be caused by the time required for adaptation of the parts to make them fit, or work onsite may even be interrupted while new duct parts are fabricated offsite (work on typical apartments was not continuous – the dateline shown at the bottom of the figure indicates the interruptions.

The curves presented in Figure 6 and Figure 7 demonstrate that accurate short-term analysis of flow progress can not be obtained using the "earned value method." Estimation of remaining activity duration requires understanding of the nature of productivity variation, which is due to mobilization time, set up period, and the number of distinct returns required. However, an additional factor is at play: the intermittent nature of the flow of the apartment *'product'* through the *'workstations'*. To explain the reasons for this re-entrant flow, the flow of the trade teams through the building must be examined.

TRADE FLOW

Figure 7 shows that the majority of work was performed continuously within 3 working days, but after that, the crew returned to work within this apartment one day each week over the subsequent period, as called for due to progress by the other trades. On each return, the workers fitted and installed a few duct parts and took measurements for fabrication of other parts. The HVAC works in this apartment were finished during August, 2006: the detailed record shows that members of the crew returned to the apartment on no fewer than 13 separate occasions.

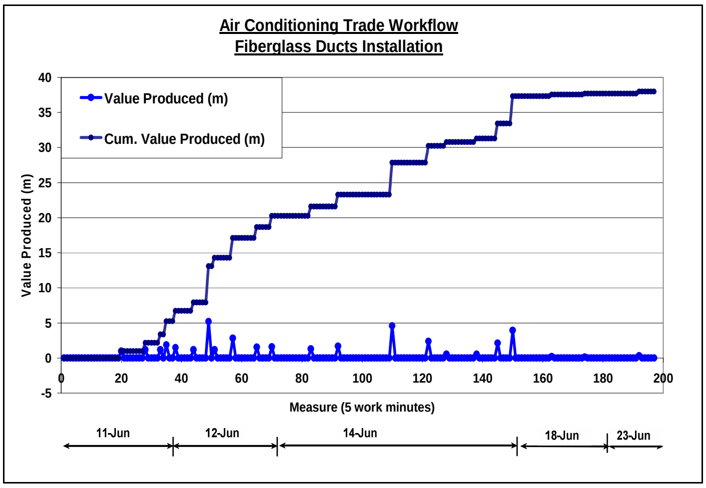

Figure 7: Workflow of HVAC trade through installation of fibreglass ducts within an apartment

Return of the air conditioning crew several times to the same location produces a local loop of trade workflow, defined above as 're-entrant flow'. Figure 8 presents the actual flow of the HVAC crew through apartments in the building during a three month period. The team split and recombined, worked in more than one location at the same time, and returned several times to various locations. Partially the flow re-entrance or 'turbulence' is caused by improvident planning and failure to ensure that all the prerequisites are satisfied, which resulted in excessive splitting of work packages, and wide rework.

However, there are also 'inherent' factors. Each finishing activity comprises a set of tasks and sub-activities. The plumbing trade (installation of water and sewage systems), for example, enters each apartment according to plan at least 10 times: 1) install sewage pipes; 2) install water pipes; 3) extend sewage pipes into bathrooms; 4) install sprinkler system; 5) temporarily block in-floor sewage pipes; 6) extend sprinkler pipes down; 7) install drain for air-conditioner; 8) install sprinkler heads; 9) install bath and connection to drain; 10) install taps and other bathroom appliances. Such sub-activities are predictable and in theory could be considered in detailed short-term planning. Thus, the re-entrance of this trade can be mapped.

However, there is also a wide range of relatively short operations, such as pressure-testing of the water supply system after installation; extension of pipes, etc. that cannot be rigidly scheduled because their execution time is dictated by external inspectors or the needs of other trades. They also require fewer resources than the standard operations. In this situation the flow of labour through a particular location is interrupted, and crews sometimes split to perform more than one activity simultaneously.

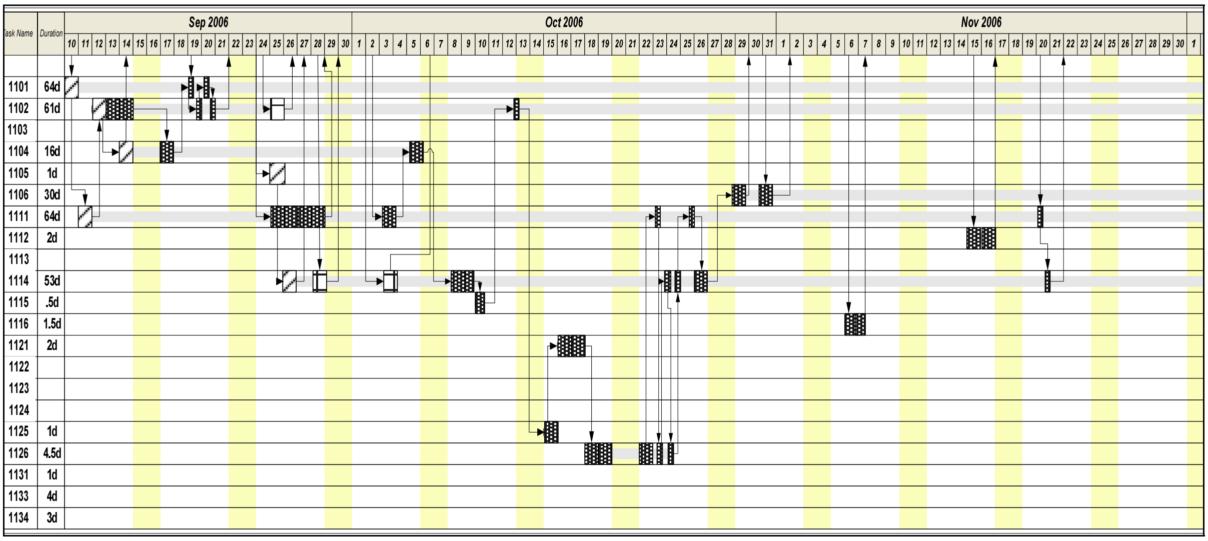

Figure 8: The flow of the HVAC crew through the apartments in the building.

FLOW CONTROL

As discussed above, at the master plan level, finishing activities are grouped in sets and the desired production rates are defined for each set of activities enclosed in summary tasks (as shown in Figure 5). The next project planning level in this project was done in weekly meetings of the project manager with the main work managers, during which weekly work packages were assigned to each trade. We should note here that the LPS was not adopted in the project, thus the weekly meetings provided only construction-related assignments, omitting analysis of constraints and the 'make-ready' process. Due to the high variability of labour capacity flow, fragmentation of progress status information, and lack of analytical tools to support short-term flow forecast and analysis, such meetings proved ineffective in coordinating trades at the operational level. As a result, final coordination between trades relied completely on the crews themselves negotiating with one another, on an hour to hour basis. In many cases crew members were observed moving through the building to look for available work. In terms of Job Shop Scheduling, this situation may be thought of as a workstation proactively 'pulling jobs to itself' to process according to its own criteria for optimum processing. This is possible in the execution of finishing works in construction for two reasons: the '*workstations*' are mobile and some technological precedence constraints between tasks are loose.

The absence of any centralized system or other policy to determine trades' navigation through the building only increased production fluctuations. The following results were observed: irregular and often unexpected occupation of locations, unbalanced and ineffective utilisation of labour, excessive release of works for execution, and accumulation of WIP. In order to absorb uncertainty and variation in the release of work, the subcontractors themselves subcontracted work to independent teams, which made labour flow increasingly less predictable and controllable. Continuous labour turnover made the learning effect irrelevant, and all these finally adversely affected the quality of the work.

CONCLUSIONS

It was previously discussed, and the case study demonstrates, that the traditional scheduling and control techniques using CPM, are inappropriate for day to day management in construction. In CPM, the tasks are most commonly represented by nodes in networks, which are 'black-box' representations of the parameters that define the behaviour of the activities within the whole project. This is a limiting conceptual model because it cannot describe the nature of construction processes realistically, it cannot represent nonlinear production rates, it cannot model interdependent durations, and it cannot describe flows of resources through locations on site. As a result, CPM tools do not provide adequate support for analysis of constraints at the operational level.

The re-entrant pattern of flow of finishing operations has many similarities, but more differences, when compared to the Job Shop Scheduling Problem of semiconductor manufacturing. For these reasons, the experience of manufacturing scheduling cannot be directly applied for real-time allocation of construction resources. The survey of solutions applied to semiconductor job shop situations indicates that due to the complexity of the problem, real-time scheduling can best be achieved through application of appropriate heuristics (dispatching rules) to each particular workstation, rather than any kind of central control model.

Given the deeper complexity of the construction trade flows, it appears therefore that development of relatively simple heuristic rules appropriate for different situations of construction workflows, holds promise as an approach to achieve trade team flow behaviour that works toward overall project flow objectives rather than undermining them. The heuristic rules should direct the activity of each trade team at each junction in its working day, determining the priorities with which it selects assignments from a pool of possible actions already filtered through a make-ready process.

The heuristics used in semiconductor manufacture provide a starting point, but other sets may be devised to achieve lower WIP, shorter cycle times and less re-entrant flow in different contexts that may arise in construction. The next steps of this research will involve application of rule sets to dispatch a backlog of pending assignments. The impact of each set on short-term project progress will be examined by discrete event simulation, with the goal of determining the criteria for selection of the better heuristics for guiding the physical flow of work teams in different situations.

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