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UNDERSTANDING SCHEDULE UNRELIABILITY: CASE STUDY ON A FACILITY-TOOLING PROJECT

ABSTRACT

Prior to any facility-tooling project start, schedulers develop a master schedule that sets out the tool arrival dates on site. The lags between the moment when this schedule is developed and the dates scheduled for each tool arrival increase proportionally to how late the latter are scheduled. Schedulers frequently update the schedule if suppliers fail to meet the milestones. The extent to which scheduling then follows operations or operations follow the schedule may be hard to tell. This paper delves into this phenomenon by means of analyzing data from one facility-tooling project. This data is at the basis of current efforts to develop a system dynamics model of a facility-tooling project that brings together critical scheduling and operational variables.

I.1. INTRODUCTION

Prior to the start of a project to tool up a semiconductor fabrication facility (fab), schedulers develop a master schedule in light of the information they have at hand. This schedule captures the dates when tools are expected to arrive to the unloading docks on site, and the activities and resources needed for moving and installing the tools into the fab. Scheduling efforts help the project team to anticipate potential problems and plan accordingly. Schedulers typically use off-the-shelf software packages that express a project as a deterministic network of activities (e.g., Microsoft Project®, Primavera Project Planner®). Scheduling tools allow users to visualize the project as a chart of series of interconnected bars and milestones. These charts capture the early and late activity start and finish times, the precedence relationships between activities, and specific project milestones such as on-site deliveries by suppliers. Scheduling tools also allow schedulers to allocate resources to each activity and to use the critical path method (CPM) for identifying the series of activities that will take longer. In addition, schedulers can use complementary software packages for associating probabilistic distributions to the activity durations and assess the schedule with probabilistic methods, such as the Program Evaluation and Review Technique (PERT) and Monte

Carlo simulation. Scheduling tools support project planning processes in a variety of industries, such as in construction, software development, and manufacturing.

Project schedule reliability is desirable. Yet, despite the sophistication of current tools, schedules more often than not prove to be unreliable due to diverse reasons, such as: (1) the development of excessively detailed activity-networks when information available is scarce, when the critical project participants may not be all selected, and when the conditions of the production environment ahead are still unknown; (2) the need to change the project criteria or scope throughout project development; and (3) the difficulties in predicting accurately the actual rates of project execution (e.g., Laufer and Howell 1993, Tommelein 1998). Activity-based schedules have other limitations even if they would be developed to a level of detail consistent with available and reliable project information. These limitations relate to: (1) inability to capture information and material flows between activities; (2) inability to express constraints in terms of shared resources; and (3) lack of flexibility to adapt to changes, admittedly difficult to anticipate, in project scope and design criteria (e.g., Sawhney and AbouRisk 1995, Chehayeb and AbouRizk 1998, Lyneis et al. 2001). As a result, problems of schedule overrun are hard to prevent and pervasive in the management of projects.

This paper presents a case study related to the scheduling process of tooling up a greenfield fab. The purpose of study is to sharpen understanding on the phenomenon of scheduling unreliability in fab-tooling projects. The paper is organized as follows. After reviewing literature on scheduling methods and case studies, the paper describes the logistics involved behind tooling a fab. Then, it discusses the sources of uncertainty and complexity that cause scheduling unreliability in fab-tooling projects, and provides evidence of procedures adopted by organizations to mitigate that effect. After, the paper analyses scheduling data collected from one fab-tooling project. Finally, the paper introduces current efforts to develop a system dynamics model of a fab-tooling project that brings together critical scheduling and operational variables.

I.2. RELATED WORK

Researchers have long studied the problem of the lack of flexibility and reliability of activity-based scheduling methods to support planning processes in dynamic project environments (e.g., Higgin and Jessop 1965, Laufer and Tucker 1987, Laufer and

Howell 1993). Research in the construction management domain has primarily focused on delivering prototypes of scheduling methods that would perform better in conditions of uncertainty. Fischer and Aalami (1996) and Dzeng and Tommelein (1997), for example, take advantage of electronic and object-based descriptions of designs, schedules, and estimates, to support the reuse and automated generation of realistic schedules. Ben-Haim and Laufer (1998) propose a conceptual tool that incorporates subjective information in activity-based scheduling processes whereas Chehayeb and AbouRisk (1998) and Pean-Mora and Li (2001) explore the applicability of systems simulation to support innovative scheduling methodologies. Recently, Choo et al. (1999) implement the lean principle of the last planner to improve scheduling and planning reliability at the micro level of construction work assignments.

Research in the domain of system dynamics to support strategic project management is closer to the work presented here. For example, Abdel-Hamid and Madnick (1989) observe that in the early life of a software development project, if execution falls behind the initial schedule, managers will tend to hire more resources or to promote overtime for attempting to hold to the original schedule. In the late stages of the project, if execution falls behind, the likelihood that managers will extend the original schedule increases. Later, Abdel-Hamid (1993) presents a hybrid model that integrates a system dynamics project simulator with algorithmic estimators. Abdel-Hamid (1993) assumes project execution will always differ from the master schedule, and accordingly advocates that schedule estimation should be a continuous process enhanced through feedback data collected from project control. Recently, Lyneis et al. (2001) present a case study in which a system dynamics model was used to assess the benefits of alternative organization and process structures for delivering projects in an aerospace company, a purpose similar to that of the work presented here.

I.3. CASE STUDY ON A FAB-TOOLING PROJECT

I.3.1. SEMICONDUCTOR TOOLS

A semiconductor tool consists of a set of equipment parts, whose total number varies from tool to tool. The dimensions and weight of each part also vary. Tools tend to have names that match their functionality—such as etchers, steppers, electroplaters, furnaces, and implanters. They are developed and manufactured by different vendors, whose engineering and manufacturing facilities are scattered around the globe. For instance, a fab under development in the state of California, U.S.A., may receive tools from suppliers based in diverse states in the U.S.A., or in Japan, Israel, and Europe. A tool is ready to be shipped to the semiconductor fab once it successfully passes the qualification tests performed by the client in the suppliers' plant. Shipments can get delayed in relation to the initial schedule for different reasons, such as:

- the client defers issuing a purchase order and consequently the vendor refuses to ship the tool;
- decontaminating and palletizing the tool lasts longer than initially expected: every tool, before being shipped, needs to be properly cleaned, packaged, and palletized to be protected from trepidation and air pollution during transportation; packing is typically done in the facilities of a crating company;
- shipping a tool ─ by truck (large tools, for example, come in 4 or 5 trucks), or by plane or by ship if they come from overseas ─ is prone to unexpected delays such as inclement weather conditions;
- customs clearance, a process which involves the freight carrier, the tool vendor, and the tool buyer, can last longer than expected; for example, when tools come in separate parts, customs may only give clearance once all the parts arrive; delays may also occur if customs consider documentation or payment is missing.

Once a tool arrives on-site it must be unloaded, uncrated, moved into an environmental controlled room (which keeps a differential atmospheric pressure with the exterior so dust particles move towards exterior), cleaned, and moved in to its final position. Diverse resources must be available to unload a tool: (1) a crew of movers; (2) an unloading dock; (3) steel tripods to reinforce the cleanroom floor along the path the tool will follow to its final position; (4) equipment to move the tool, such as an elevator or a forklift; (5) equipment to reinforce the floor at the final location of the tool (e.g., steel tripods for light tools, steel pedestals for heavy tools, or special air tables for some tools); and (6) space: movers must be provided a priori with accurate information on the weight and on the dimensions of the tool parts so they can plan the moving path and arrange the necessary equipment.

A move-in crew is typically composed of 10 pipe fitters, of which 5 stay at the unloading dock and 5 stay in the cleanroom, the latter wearing special suits. A large tool takes on average 10 hours to move in, a medium tool 5 hours, and a small tool 3 hours. During the peak of a recent tool install project, three move-in crews were present on site. Tools can only be unloaded if all needed resources are available. Unloading delays represent added direct costs (e.g., idle labor and equipment, demurrage costs in the port or airport warehouse, daily fees in a carriers' warehouse) and impact the work planed.

I.3.2. TOOL INSTALL PROCESS

Tool install comprises the installation of tools in the fab's cleanroom (a room in which air quality and temperature are rigorously controlled), and the installation of the support equipment for each tool in the subfab, the space underneath the cleanroom. The number of main tools to install in a cleanroom frequently ascends to more than one hundred, and each tool has to hook up to several utility routings and support equipment. Chip manufacturers frequently pressure vendors and contractors to accelerate tool delivery and installation because the manufacturer that gets ahead in research and production benefits from higher profit margins when the chip products reach the market. In greenfield projects, fab-tooling starts when the fab building is completed enough so the tools can be moved safely into the cleanroom and the support equipment moved into the subfab. (In brownfield projects new tools are constantly arriving on site to replace existing tools—the complexities of installing tools in fabs with ongoing production fall out of the scope of this case study research).

The design of the tool install work involves a team composed primarily of engineers (structural, electrical, mechanical, and chemical), and an architect. Tool install designers need preliminary information to be provided by the tool vendor. The tool install design guides the construction trades in their work. Tool installation is primarily performed by pipe fitters, sheet metal workers, and electricians. An architect contractor also gets involved in removing the floor tiles and wall partitions before the tool is moved in to its final position, and in fixing the floor tiles and wall partitions around the tool once its installation is complete.

The process of installing a tool is often decoupled in two sequential phases: pre-facilitation and final hook-up. Pre-facilitation can take place before tool arrival. It consists of connecting the main routings of the utility systems that run in the subfab (including pipes, ductwork, and cables) to the space underneath the cleanroom waffle slab, above which the tool will be located. Contractors can pre-facilitate all the routings but for the last 5 feet. The installation of the last 5 feet is done during the tool hook-up phase once the tool and its support equipment have moved into their final positions. Before hook-up starts, designers must give contractors detailed information about the system that will physically support the tool in its final position so contractors can procure it. Supporting systems can be, for example, a custom manufactured steel pedestal or common steel tripods. Once fabricated, pedestals will have to be painted, approved by tool install designers, wrapped, and shipped to the construction site.

Hook-up follows pre-facilitation and involves, first, moving all the parts of a tool from the unloading dock to the positions marked on the floors of the cleanroom and of the subfab; and then, connect the utility valves at the tool with the points of connection left underneath the cleanroom waffle slab and with the points of connection at the support equipment. After hook-up, contractors (jointly with tool engineers) must proceed with diverse safety qualification tests before tool installation is considered finished from a construction standpoint. Safety tests will check the soundness of the electrical installation, and of the inert and non inert gases installations, and will also include an inspection by a city official.

I.3.3. PROJECT UNCERTAINTY AND COMPLEXITY

Scheduling a fab-tooling project is a complex process because various sources of uncertainty affect the dates when each tool is required to arrive as well as affect the tool install design and tool installation phases. Requested tool dock dates are often unreliable since these are frequently set out when the tools are still being engineered and manufactured in the vendors' facilities. Moreover, since the arrival of tools is spread along several months, the length of time between the moment when the tool requested dock dates are set out and the date when each tool is expected to arrive on site varies from tool to tool. Intuitively, the reliability of requested tool dock dates decreases as this planning horizon increases. Regrettably, master schedules do not explicitly acknowledge this phenomenon.

The risks of having to rework the tool install design and the tool pre-facilitation tasks are also significant because the installation tool requirements can change in relation to the preliminary information handed off to designers and contractors. These changes can involve the set of utilities or the utility capacities required by the tool, and they are particularly frequent throughout the development of the first tools in any new technological cycle. Expected tool location in the cleanroom may also change, which can be extremely disruptive if the tool was already pre-facilitated. In addition, if a tool arrives late, the space that contractors initially planned to use for its installation may be obstructed by the routings connecting other tools that were installed in the meantime. Practitioners argue that the time apparently gained by pre-facilitation offsets the risks of having to rework design and installation in the event tool installation requirements change but data is unfortunately not available to prove their conviction.

The complexity of the organization that must be put together to manage a tool install project is another source of uncertainty. In a recent project, on the client’s side, more than ten area coordinators shared the responsibility for the installation of tools, each coordinator in charge of a specific area in the cleanroom, such as lithography, etching, or wafer testing. Several tool managers, each one in charge of all information exchanges and negotiations with a few tool suppliers, reported directly to each area coordinator. Issues to report involve for example the technical features of a tool, the tool arrival dates, the tool qualification tests, the shipping method, the price and warranties, and the issue of a purchase order. Different people have different negotiation and management skills. These skills affect their ability to timely share updated information with people responsible for designing the installation and for installing the tools.

Finally, uncertainty also stems from the large-scale nature of a tool install project. The number of equipment pieces that will be unloaded on site to equip a greenfield fab can easily reach 3,000 units. Of these 3,000 units, 10% to 15% will cost more than $100,000 each; approximately 5% of 3,000 will be the extremely costly and sophisticated semiconductor tools (such as ashers, steppers, sputters, copper electroplaters, polishers, scanners, trackers, and wafer inspection systems). These 150 tools may all arrive to the unloading dock within less than 8 to 10 months. The average price of a tool in this 5% percentile can reach $4 million, with the most expensive tools costing more than $10 million each (in current costs for year 2000). In contrast, approximately 75% of the 3,000 pieces of equipment will have prices under $15,000 each, including printers, monitors, glove storage racks, vacuum wands, pump lift carts, digital voltimeters, bar code gun holders, ergonomic chairs, etc. The reality is that procurement, shipping, and unloading of more than 3,000 pieces of equipment, whose total cost may ascend to almost 1 billion dollars, will have to be tracked and managed in less than one year.

I.3.4. DATA ANALYSIS

Figures 1 and 2 illustrate the way the requested tool dock dates slipped in a project that consisted of installing 140 tools in an initial time window of 7 months. Figure 1 shows that the oscillation in the tool arrival weekly rate was significantly higher than that initially scheduled. Scheduling unreliability was due to several reasons, such as: (1) the tool vendor committed on an early requested dock date but was not able to meet that date; (2) the tool did not pass the qualification tests conducted at the vendor's facilities and as a result its shipping was delayed; and (3) the tool was manufactured on time and passed the qualification tests but experienced shipping delays (e.g., tools are identified by numbers and, occasionally, inconsistencies between the tracking numbers used by carriers, vendors, and the client may delay the shipment).

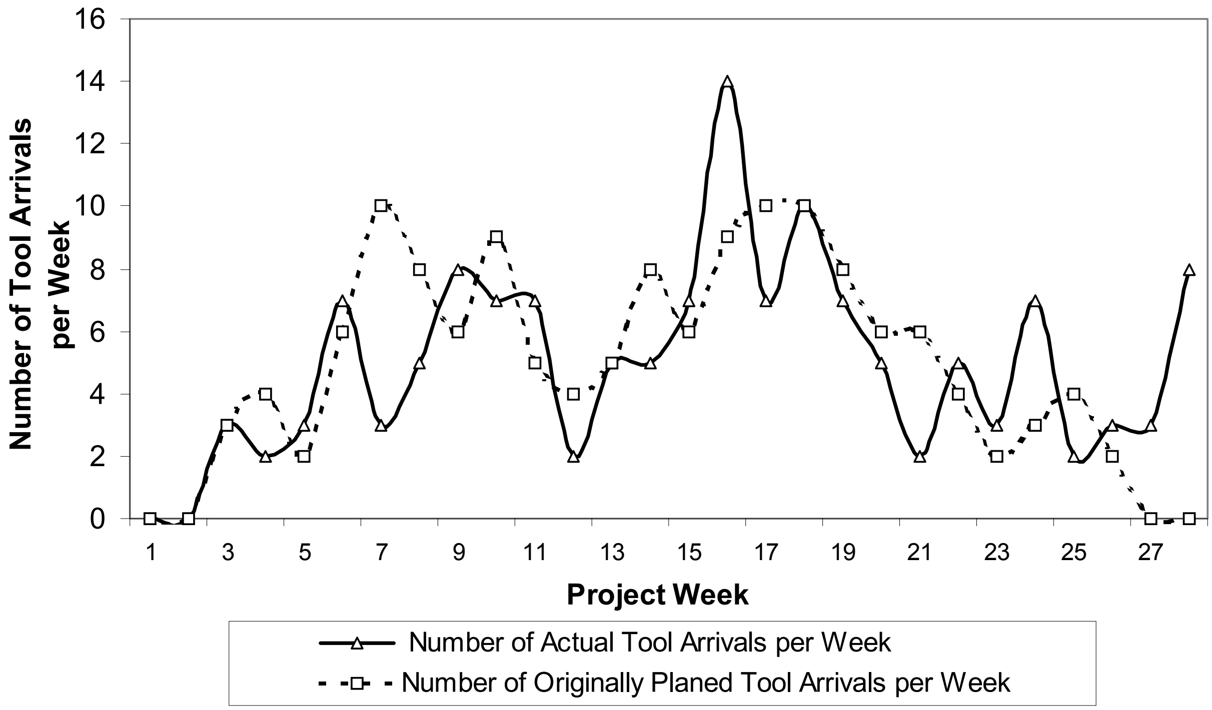

Figure 1- Planed Tool Arrivals versus Actual Tool Arrivals

Figure 2 shows that the difference between the number of tools onsite on a specific week and the number of tools originally planned to be onsite on that same week reached about 10 tools by week 8. This difference progressively increased throughout the project to peak at 20 tools around week 21 resulting in that the project finished three weeks beyond the original plan.[1]

In this project, the schedule was weekly updated. Figure 3 illustrates the reliability of the requested tool dock dates, depicted as if all tools had arrived in the same week (week 0). A positive difference between the planed and actual tool arrival dates means that the tool arrived later than the date scheduled in a particular week, a negative value means the tool arrived earlier than scheduled. The number of tools depicted decreases as the planning horizon increases (i.e., as the time interval between the moment when the initial schedule was set up and the date of the tool arrival increases) because scheduling information prior to the tool arrival dates gradually ceases for the first tools to arrive.

[1] Three weeks late can be detrimental to project profitability in fab-tooling projects

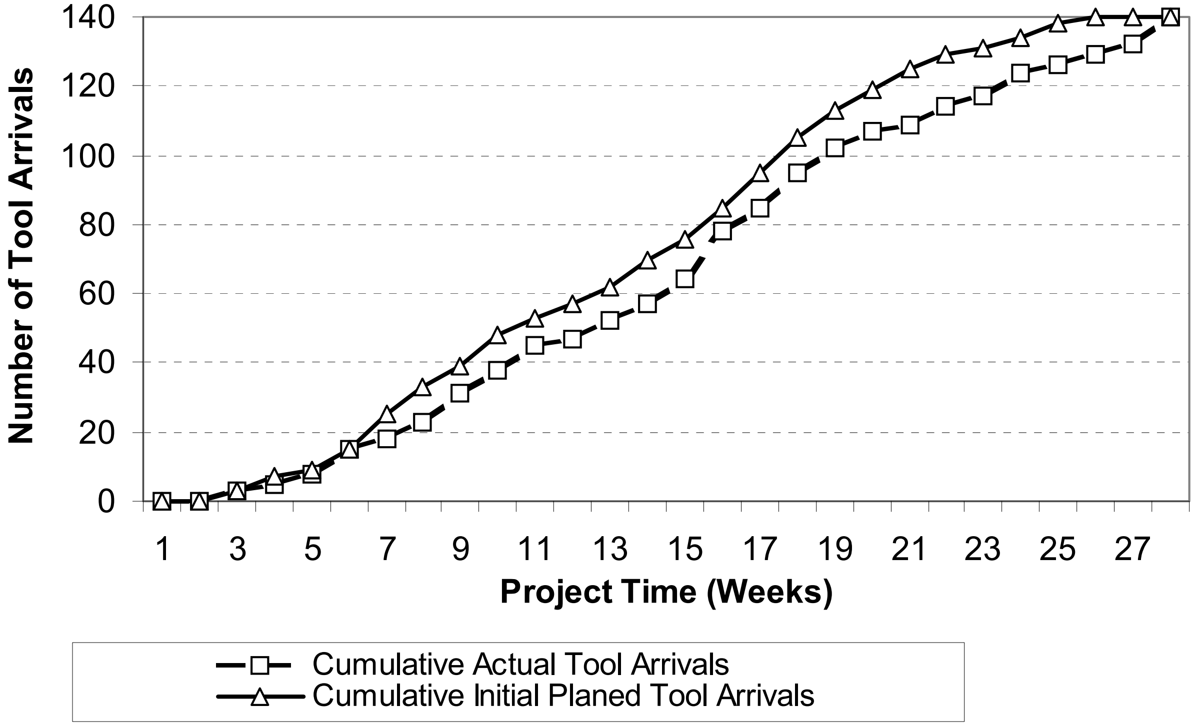

Figure 2 - Cumulative Planed Tool Arrivals versus Actual Tool Arrivals

Figure 3 shows that some requested tool dock dates were fairly reliable even in the long term, whereas other dates were far too early and slipped in the course of time. (It is interesting the fact that the tools that exhibit scheduling processes more reliable were manufactured by Japanese suppliers.) Occasionally, some tools arrived earlier than scheduled, which can be as disruptive as a late tool arrival. It is unclear the extent to which some tools were brought earlier to keep construction gangs busy considering that other tools were delayed. The fact that not all tools show a null difference on week zero means that the schedule information was not always kept updated ─ the tool arrived on a particular week but the last updated schedule showed the tool as arriving on a different week. It is worth noting that Figure 3 suggests that the majority of the requested tool dock dates significantly slipped – frequently more than 60 days – into reliable new requested dock dates in the first 2 to 4 weeks after the project started. This fact indicates that a major effort to align the initial schedule with more realistic project expectations occurred in the first month after project start. This effort was successful in the sense that the resulting requested dock dates, even if they changed more times afterwards, already stayed close to the actual tool arrival dates.

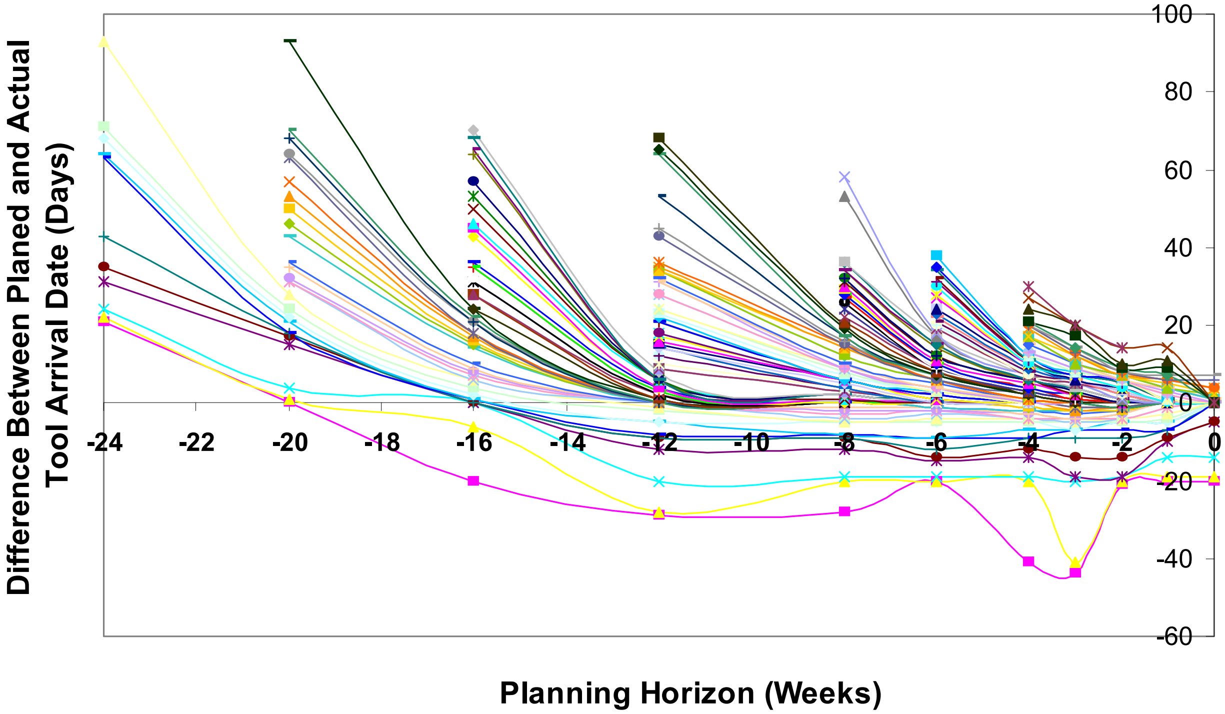

Figure 3 - Evolution of Requested Dock Dates According to Planning Horizon

Figure 4 illustrates the distribution of the frequencies corresponding to the number of changes in the requested tool dock dates. It shows that slightly more than 80% of the required tool dock dates changed throughout the project and the vast majority of tools had its requested dock date changed one up to four times before it arrived to site.

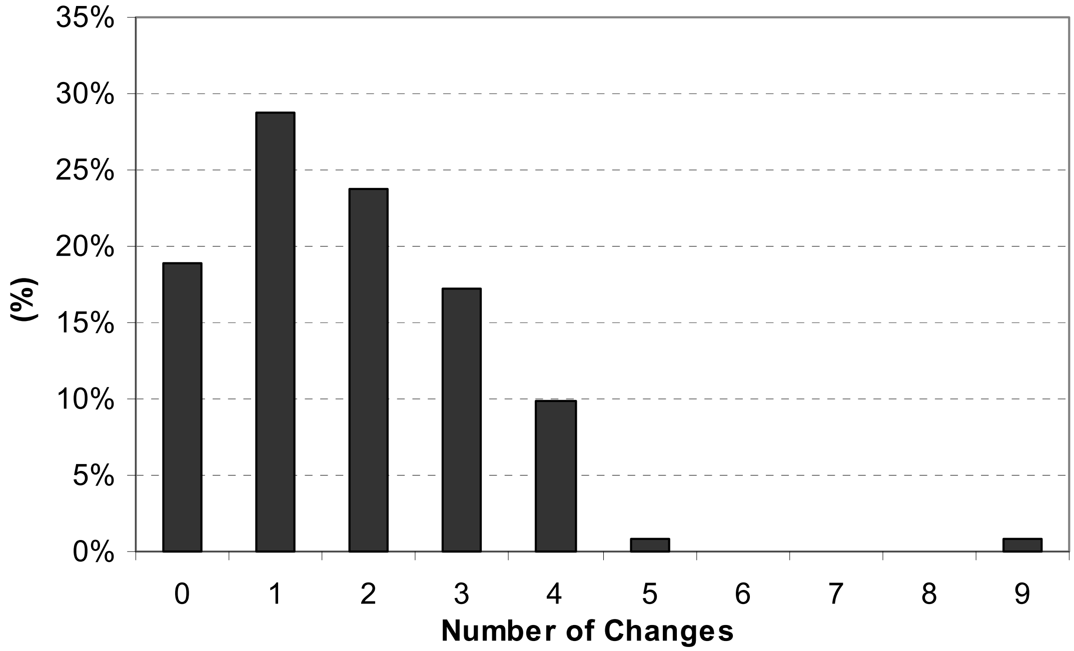

Figure 4 - Frequencies of Changes in Requested Tool Dock Dates

(Sample of 122 tools)

I.4. SYSTEM DYNAMICS MODEL

The objective of this research effort is to develop a system dynamics model that captures the key cause-effect relationships between variables descriptive of the scheduling process of a fab-tooling project and variables descriptive of the actual operational processes for manufacturing, shipping, and installing the tools. The model presented next results from early efforts in this regard. This model is largely based on preliminary data collected and on understanding gathered during the case study research. Clearly, this information is insufficient in relation to the information necessary to accomplish the final research objective. As a result, the model in Figure 5 does not yet include the representation of the manufacturing, shipping, and fab-tooling processes. Instead, the model only captures at this stage the dynamic interactions between two key variables in scheduling a fab-tooling project ─ the "Initial Scheduled Tool Arrival Rate" and the "Updated Scheduled Tool Arrival Rate" ─ and an operational variable ─ the "Actual Tool Arrival Rate". Accordingly, the two top flows in the model relate to information and the bottom flow relates to the physical tools. A detailed description follows.

The “Initial Scheduled Tool Arrival Rate” expresses the initial weekly scheduled rate throughout project development set up by the client jointly with the suppliers before the project start, and is read from a look up table. This rate flows into a stock called “Initial Scheduled Tools On-Site” that expresses the number of tools initially scheduled to be on site at any time. The stock “Scheduled Tools to Arrive” accumulates the tools that are scheduled to be on site at any time, according to the “Updated Scheduled Tool Arrival Date”; this rate reflects an update of the “Initial Scheduled Tool Arrival Rate” based on a control mechanism explained below (the “Accelerate Loop”) and on a “Schedule Reliability Adjustment Factor” (this factor allows to slow down the scheduled tool arrival date based on suppliers’ feedback not yet included in the model). The stock “Scheduled Tools to Arrive” is depleted by a “Scheduled Confirmed Tool Arrival Rate”, which is based on the actual “Tool Arrival Date”. The stock “Scheduled Confirmed Tools On-Site” reflects the number of tools on site at any time according to the updated schedule, which is not necessarily equal to the precise number of tools on site due to an eventual delay in the process of communicating information. The stock “Tools On-Site” accumulates the number of tools that have effectively arrived to the job site at any time, according to a “Tool Arrival Rate”. The factor “Execution Adjustment Fraction” models the inability of the suppliers to deliver the tools even at the “Updated Scheduled Tool Arrival Rate”.

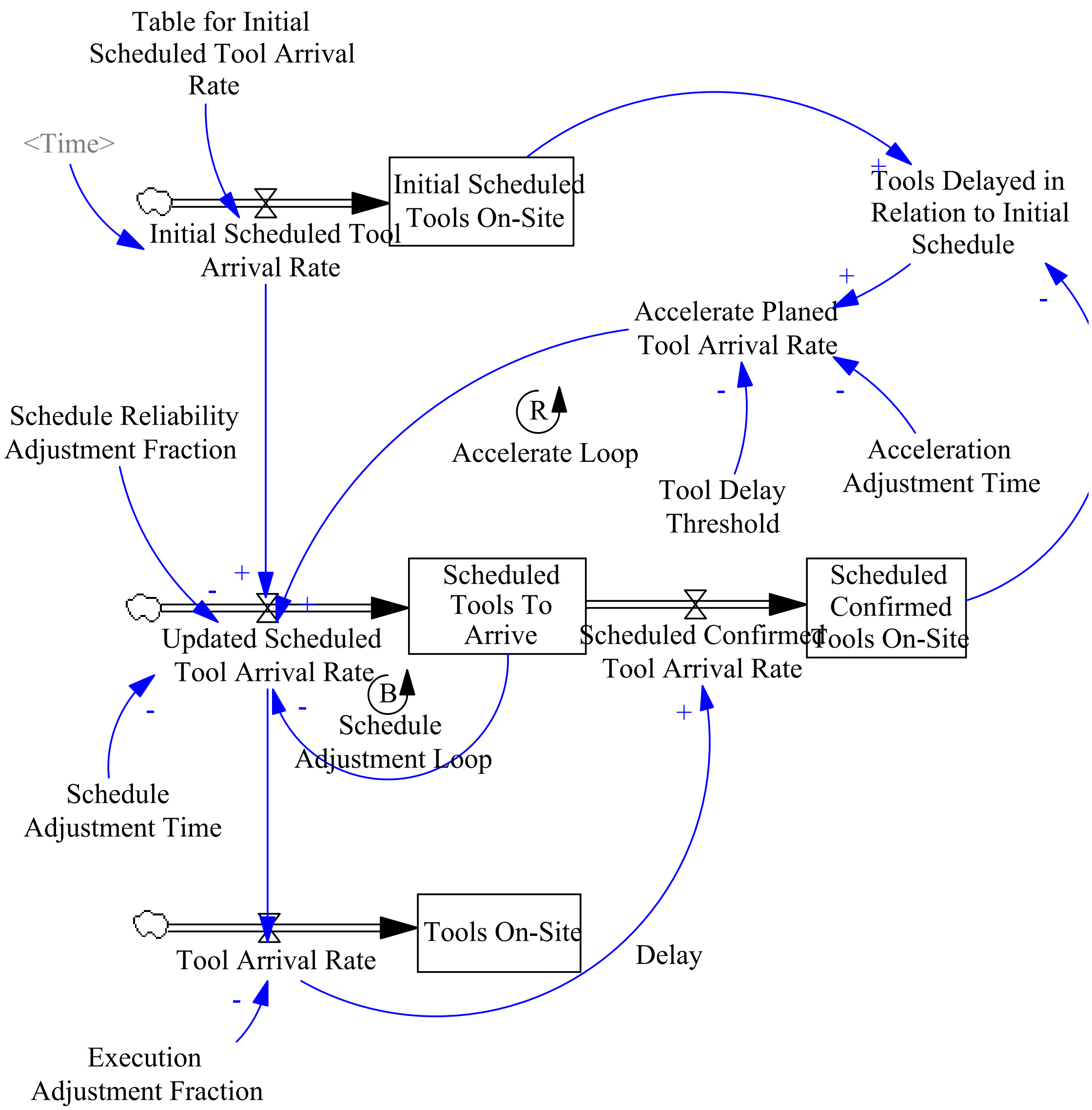

Figure 5 - System Dynamics Conceptual Model

A balancing loop was implemented in the model. Accordingly, an increase in the stock "Scheduled Tools to Arrive" (if tools were actually arriving at the updated schedule rate this stock should have a value closer to zero) affects negatively the "Updated Scheduled Tool Arrival Rate", at a rate adjusted by the variable "Schedule Adjustment Time". This balancing loop reflects the observed practice of regularly updating the project schedule to keep it aligned with the actual tool arrival rate. This practice is similar to the notion of floating goal (Sterman 2000, p.532). A goal adjustment rate acts to eliminate the discrepancy between an original plan and the reality by eroding an initial exogenous goal. Specifically, the more unreal the goal, in this case the harder to meet the “Updated Scheduled Tool Arrival Rate”, the higher the chances are that the “Tool Arrival Rate” may fall behind, which increases the need to slow down the “Updated Scheduled Tool Arrival Rate”.

Diverse control mechanisms can be implemented in the system as they may exist in the real world. Figure 5 shows a mechanism that assesses the “Tools Delayed in Relation to Initial Schedule”. This control mechanism assumes that despite the fact the organization is constantly updating the tool arrival schedule rate, it retains memory of the initial project schedule in terms of the cumulative number of tools that were supposed to be on site at any week. Thus, whenever the work delay exceeds a “Tool Delay Threshold”, the client would look for accelerating the “Updated Scheduled Tool Arrival Rate” up to an “Accelerate Planed Tool Arrival Rate”, within an “Acceleration Adjustment Time”. This “Work Delay Threshold” can be a constant or can vary along time.

I.5. DISCUSSION

The dynamic hypothesis at the basis of this model states the following. An overly optimistic master schedule may detrimentally impact the fab-tooling process. This impact can be to an extent that the fab-tooling project lasts longer than the duration it would hypothetically last if a more realistic schedule had been adopted from start. An overly optimistic schedule means here that, first, suppliers were forced to agree on tool requested dock dates that they knew would be extremely difficult to meet but decided to agree anyhow in order to get the job. Second, tool install designers and contractors were instructed to do extensive pre-facilitation work based on preliminary information provided by suppliers. The operational impacts may relate, for example, with having to rework pre-facilitated work because the input information was unreliable; with tool install lasting longer than initially planned because on site conditions changed; and with lacking available resources on site to move and install tools because of unexpected peaks and valleys in the tool arrival rates.

The boundaries of the current model need however to be expanded before the model can be used to test the dynamic hypothesis. Expansion should include, first, the decision-making processes in the client, tool supplier, and contractor organizations and the way these processes react to discrepancies between the actual and the scheduled tool arrival rates. Specifically, the model needs to capture: (1) the extent to which a tool requested dock date can fall behind or ahead the original schedule; (2) the way organizations agree that a requested dock date is unfeasible and needs to slip; and (3) the process of deciding whether to pay premium shipping or pre-facilitate a tool for accelerating the delivery and installation processes.

Second, the model needs to be expanded to include the key operational tasks in a fab-tooling project (e.g., tool fabrication, tool shipping, tool installation, tool qualification test). The model can then express the way these tasks are affected by the scheduling decisions, for example: (1) the extent to which suppliers accelerate tool delivery processes (e.g., working overtime); (2) the extent to which accelerating tool delivery affects the success rate in the tool qualification tests; and (3) the extent to which changes in the requested tool dock dates affect the rework rates of tool install design and tool install onsite.

Third, the model needs to include key resources and possible capacities, such as the number of available docks, move-in gangs, and tool install gangs, so the effects of alternative scheduling strategies can be assessed with different organizational structures.

To expand the model, data will need first to be collected by means of interviews, observations, and analysis of project records. Once the model has been expanded, it will need to be calibrated to replicate available data. Then, the model can be used to investigate the effectiveness of alternative scheduling strategies and control mechanisms for helping organizations to cope better with uncertainty in fab-tooling projects.

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