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Measured Mile Analysis and International Mega-Projects

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An accurate calculation of labor distribution and loss of productivity costs by contractors is frequently complex and almost always a challenge for project management. Recent advances in measured mile and demonstrated labor efficiency calculations (DLE) methodologies, as well as court decisions attesting to their reliability, have added an important and persuasive tool to the cost engineer's tool chest. However, attempts to apply these tools to complex mega-projects, in which thousands of workhours and units of material are logged and installed, are, in the eyes of many cost engineers, destined for failure. Not true! Quoting from *The Godfather II*, such applications become "difficult, but not impossible."

The new Hong Kong International Airport was one such mega-project, a construction effort in which contractors and engineers from thirty nations worked together to build an award winning, one-of-a-kind international airport with supporting infrastructure. This $25 billion project, including the world's largest terminal, a 16.6 square km island, runways, and road and transit connectors to downtown, challenged all project participants. It clearly presented a daunting problem to the quantity surveyors and programmers (cost and schedule engineers) who were tasked with maintaining accurate and complete records of units of work, costs, workhours, and variations, all of which were in several languages and currencies. The task of the cost and schedule engineers was made more difficult when, during the postconstruction period, they were called upon to "prove-up" loss of productivity and worker inefficiency costs caused by variations, delays, design changes, and differing work conditions.

The ultimate solution to those problems on this mega-project, and for the parties attempting to resolve its disputes, was the development of a series of complex and linked databases that collected and tracked workhours, installed-units, actual costs, and calculated DLEs and earned values on a daily basis, all with a degree of accuracy required by an arbitral tribunal. The results of these efforts were to apply DLE calculations to terminal areas in which DLEs could not be directly calculated. This paper discusses one such DLE calculation, one created for the terminal building's exterior glass cladding and curtain wall, as a model for the successful application of this method of analysis.

THE HONG KONG AIRPORT TERMINAL PROJECT

The passenger terminal building at the new Hong Kong International Airport at Chek Lap Kok is an immense structure, containing the world's largest enclosed space. The building itself is a complex of eight levels, with an overall length of 1.3 km and a maximum width of 0.7 km. The roof at its highest point is 28.0 m, and consists of a series of 129 framed barrel vaults weighing in excess of 140 metric tonnes. The building's total footprint occupies over 156,000 square meters (39 acres). The roof is so large and yet relatively so light, that it behaves like an airplane wing, and accordingly was built to accommodate substantial vertical movement with corresponding flexibility at the perimeter window connections. That window wall is comprised of 53,000 square meters of cladding and glass curtain wall (see figure 1).

The $1.3 billion terminal structure was scheduled to be, and was, ultimately completed within an extremely tight timetable, requiring the use of 21 tower cranes. However, due to a variety of causes, the general contractor joint venture finished late and incurred substantial costs beyond those anticipated. Disputes were submitted for arbitration but were settled during mediation in the summer of 2001.

The authors, employees of Warner Construction Consultants, Inc., became involved with the project on behalf of the general contractor in the spring of 2000, after project completion. Our work included the preparation of a detailed schedule delay analysis of the various delays and accelerations experienced on the Project and the quantification of those costs associated with those the delays, accelerations and impacts.

THE THEORY UNDERLYING THE DLE APPROACH

The authors' initial review of the project indicated that there were substantial detailed records, and that many specific changes had been independently priced during performance of contract work. However, the vast majority of the recorded cost overruns were apparently the result of increased labor workhours that resulted from significant changes to planned execution sequences. It was clear that the arbitration tribunal would require a high level of detailed proof of costs—every claimed cost would have to be substantiated, with evidence of causation, duration, and work affected, by location, in the terminal facility.

Figure 1

Early in its performance, the authors determined that it would use, as much as was practicable, a modified measured mile methodology [2], and the more current demonstrated labor efficiency methodology [1]. Under the current demonstrated labor efficiency methodology, the determination of labor efficiency is based upon an extrapolation of actual workhours expended, or "demonstrated." The calculation requires the identification of a defined period of time and a specific location where the labor workhours and units measured reflect an efficient, unimpacted, or least-impacted, progression of the specific type of work being analyzed. Flawless data are rarely available, for either units or workhours, but their absence does not undermine a calculation where data collection and categorization are carefully managed.

Using such a "selected base test segment," the quantity of units or amount of work completed within its ascertained period (production) and the recorded workhours necessary to complete the selected task, it is possible to calculate the total efficient workhours that would be required to complete the specific type of work involved. From this calculation it is also possible to provide a representation of the progress, in units or workhours, that should have been achieved, or the units and workhours that could have been expected to be achieved if the work had been performed as efficiently as during the base test segment for the full period of its performance. Comparing the workhour estimate to the total actual workhours expended provides a check of the estimate's reasonableness as well as the efficiency of those workhours.

The foundation of the DLE approach is the assumption that the productivity, which a contractor achieved during the period of its best-sustained productivity over a reasonable number of days, involving a reasonable portion of the work, best reflects the productivity that could (or should) have been achieved by the contractor over the entirety of the period of performance for that task. The strength of the DLE approach extends from its use of actual productivity data. The approach eliminates the use of the estimate as the baseline for the establishment of the reasonable cost of performing the work, and therefore any criticism of the contractor for underpricing the cost of completing the project. In other words, the contractor's own pricing errors, if any, and inherent performance inefficiencies, are included within the DLE calculation. Only labor expended in excess of that DLE productivity model is ultimately considered as a claimable cost.

Typically, the following tests are applied to ensure the accuracy, reasonableness and acceptability of DLE analysis.

- Is the period selected representative of the productivity actually achieved over a sustained and reasonable period?
- Is the nature of the work analyzed repetitive, consistent, and generally similar in complexity to the remainder of the work?
- Have other impacts, including, for example, unanticipated weather and strikes, been excluded from the selected period?
- Is the actual productivity calculated reasonable?

In addition to the above tests, the criteria for the establishing of the DLE and the identification of the work most closely meeting that criteria are developed based on the following global parameters.

- The work location should be in an area unimpacted (or least impacted) by the identified and known claim issues.
- The effects of any learning curve should have dissipated.
- The job rhythm should have been established.
- Crew morale should generally not be a factor.

Within the above parameters, the authors developed literally thousands of unit, workhour, and DLE calculations within a series of linked databases. When complete, the DLE analysis identified by bay and date millions of dollars (US) in claimable costs. These DLE calculations included several different areas, engineering disciplines, and installations within the terminal.

THE DLE CALCULATION

One of the more complex DLE calculations, and perhaps the most expansive, involved the terminal's departure level glass curtain walls: 8,600 glass panels enclose this terminal level, totaling 53,000 square meters. These glass panels are erected on bowed vertical mullions varying in height to a maximum of 23 m. The complicated nature of the mullions, their extreme unrestrained height, armature connection to the roof structure, and the huge size of the glass panels resulted in the need for dozens of specialized crews to work on each aspect of the mullion erection and glass installation (see figure 2). For example, there were separate crews to perform each of the following tasks.

- Install base plates on the concrete deck.
- Alignment of base plates.
- Erect scaffolding to permit adjustment of vertical mullions and installation of the horizontal mullions.
- Erect the mullions and perform temporary attachment to the armature at the top.
- Align the mullions.
- Provide final attachment to the armature at the top.
- Erect and adjust the glass.
- Install sealant.

Figure 2

STEP ONE: AS-BUILT PRODUCTION AND IDENTIFICATION OF DEMONSTRATED LABOR EFFICIENCY UNITS

Generally, the glass panel erection contractor maintained detailed but imperfect records. They did, however, maintain very detailed unit installation and worker activity records, providing the number of material/activity units installed on a daily basis for each of 105 bays. While there were hundreds of different types of material/activity units installed at each bay, the project documents recorded the following glass panel installation activities, tracked by the number of units installed per terminal bay, per day.

- Mullion preparation.
- Glass panel transportation.
- Glass panel placement.
- Temporary clamping.
- Adjustment/alignment.
- Final clamping.
- Caulking.

One aspect of the unit/activity records required particular attention. Not all bays showed a record of actual glass panel installation. This was due either to a hold placed on work in the area, leaving the work to be performed at a later date (after the study period), or because the glass panels installed were recorded in the wrong bay. The second situation was rare, and occurred in very specific locations. These locations were typically at building corners where there were glass panels on two or three sides. In some of these corner situations, production for both bays was recorded in only one of the bays. This manifested itself in the record as a single bay having roughly twice the number of glass panels installed that was physically possible, and no record of any glass panels being installed in the adjacent bay.

Accordingly, the corner bays and other similar bays were excluded from consideration in the DLE calculations. In essence, the authors concluded that the data reported for corner bays were unreliable for the measurement of the actual work with accuracy in either of the two adjacent bays. The authors also concluded that any combination and averaging of the data between the two adjacent bays would affect their usefulness, which in fact could skew the overall results. Thus, with adjustments for unreliable data, the authors developed a detailed as-built on a day-by-day and bay-by-bay basis that recorded glass panel installation.

STEP TWO: AGGREGATION OF AS-BUILT LABOR INTO DEMONSTRATED LABOR EFFICIENCY UNITS

The contractor's labor-hour records were found not to be as detailed as the glass panel installation records. While the contractor's records delineated more than 500 different labor codes, that labor was not specifically linked to any particular bay. Therefore, the cost engineer was faced with the daunting task of organizing and reconciling the identified labor codes into the same material/activity categories as were used for recording production. Further, these same codes required allocation to the applicable work location.

Allocation was further complicated by workforce turnover and the composition of the labor crews, which varied over time. Finally, the timekeeping records were replete with minor errors for the nearly 1,000 Chinese nationals who performed the work. Again, the authors were faced with the challenge of organizing data to eliminate most reporting errors and to exclude those that could not be reconciled.

The first step was to organize the 500 different labor categories into the three aggregate labor categories to form the basis of the DLE calculations—mullion erection (performed by steel erectors), mullion alignment (performed by laborers under the direction of surveyors), and glass panel installation (performed by glass installers). This aggregation of labor codes was simplified by the use of the following criteria:

- the time of performance for each was distinct from any another;
- the actual field activities were not similar; and
- the applicable labor pool was largely separate.

Continued review of the workhour records revealed that by aggregating labor into the three DLE categories—mullion erection, mullion alignment, and glass panel installation—numerous detailed reporting problems would be eliminated. For example, some crews reported the performance of separate tasks including glass panel placement, temporary clamping, and adjustment/alignment-under the common term *installation*. Other crews reported only *placement* under *installation*. The authors concluded that these recording differences were a reflection of varied interpretations of similar task definitions rather than actual differences in the work. Therefore, through data aggregation, these reporting differences were eliminated.

Aggregation did not, however, address all labor reporting differences. For example, labor required for the erection of scaffolding is associated with each of the above three labor categories. Generally, the scaffolding was erected at the start of the work and dismantled at its completion. However, field records showed repeated erection and dismantling at certain locations during the course of glass panel installation. Still another labor category related to all three DLE labor categories was "shop" labor, which consisted of material handling and equipment operation. Consequently, neither scaffolding nor shop labor was included in the

DLE calculations. They were treated as "overhead" and applied only in making the cost calculation.

An additional problem, not unique to such analyses, was misplaced documents. Labor records for a two-week period in mid-February 1997 were lost—although the aggregate for this period was known. The authors excluded all glass installation quantities and associated labor during this period from the DLEs in order that this missing data not skew the DLE calculations.

Finally, there were labor allocation problems that occurred intermittently for certain crew groups. The individual who prepared these reports simply omitted any information for days on which glass panel installation was reported, but not its associated labor. In virtually all such cases, the labor reported for the following day included two days of labor workhours. The authors were able, by the use of cross-referencing in the database, to determine what work was actually performed because the as-built data showed installation on a day on which no labor was reported. In such situations, the authors allocated the two days of labor reported in accordance with a pattern based on the overall daily labor records. Those records showed that there were differences in the number of workers reported to be installing glass panels depending upon the day of the week, as shown in table 1.

The completed database provided a fast and accurate method for excluding data. It allowed the authors to exclude data from areas where the production figures were suspect, as well as where the labor data were inaccurate or incomplete. Thus, at the completion of this second step in performing the analysis, following the merger of these various exclusions, a substantial portion of all actual labor had been assigned. Of the entirety of the actual labor expended in performing the three categories of work reported by the contractor—mullion erection, mullion alignment and glass panel installation—between 12 and 18 percent of such was excluded from the database. Stated differently, after considering organization and allocation, the DLE calculation was based upon between 82 and 88 percent of the original available data.

In addition, a total of more than 8,500 glass panels were installed. However, 1,300 panels (8,500-7,200) installed after March 31, 1997, (the end of the study period) were not included within the database (see table 2).

Table 1

Mon	Tue	Wed	Thu	Fri	Sat	Sun	Total
15.3%	16.4%	15.4%	15.6%	15.4%	14.9%	7.0%	100.0%

Table 2

DLE Unit	As-Built	In DLE	Percentage
Mullion Erection	46,500 m^2	40,934	88.0
Mullion Alignment	46,500 m^2	38,850	83.5
Glass Panel Installation	7,200 pieces	5,917	82.2

Table 3

PRODUCTION November 19, 1996

Bay	Glass Panels	Number of Workers
407	4	6
408	55	78
421	20	28
TOTAL	79	112

STEP THREE: ALLOCATION OF LABOR BY DAY AND BY BAY

Armed with the detailed unit/activity as-built records, and the daily labor for each of the glass panel installations, the authors proceeded to allocate labor by a linear pro rata distribution. For example, the data recorded on November 19, 1996, showed that 112 workers installed 79 glass panels. Therefore, each glass panel required .71 workdays of work (79/112). The results of the allocation for this example are given in table 3.

The authors concluded that while this linear allocation of workers to location was not flawless, it did represent a reasonable and best available means by which to allocate workers. The authors recognized that on any given day the workforce for a single bay might vary but when aggregated over several continuous days, the results would be substantially correct. The product of this allocation was a data grid of 25,050 cells (75 bays over 334 days) recording labor and production. The database, therefore, contained approximately 175,000 data points for the DLE calculations associated with the departure level glass panel installation.

STEP FOUR: IDENTIFICATION OF THE DLE OR MEASURED MILE

The database detailed above also facilitated the preparation of graphic representations of this information. Two readily understandable graphic presentations were developed: one reflecting average productivity by bay—expressed in units per workday for each bay over the entire period—and one reflecting average productivity by date. Figure 3 depicts the first graphic presentation of average productivity by bay.

There were two bay groups (437 through 440, and 467 through 470) where there was consistently high productivity (in excess of one panel per workday). Based upon this data, the authors undertook a detailed review of the appropriate records, which revealed the actual events, influences, and issues that occurred or affected the work at these specific locations. This analysis showed that there was no evidence of specific contractor-caused problems at these particular locations. Further, the analysis revealed that work in these areas could be performed in a manner similar to the original plan. Stated another way, the contractor was able to mobilize its glass installers and work in several adjacent stages in a near continuous operation. Finally, there were no specific disruptions that prevented work from proceeding in a manner that most closely approximated the original plan. The original plan was known because the contractor was required, prior to the commencement of work, to develop detailed method statements that described and depicted in diagrams how each task, in this case glass panel installation, was to be performed.

A similar analysis of bays with low productivity revealed that there were often times at which specific owner-caused events negatively impacted productivity. However, the overriding conclusion was that there were few specific owner interferences that explained the low productivity. Rather, it was observed that in areas of low productivity the overall pattern of work was expansive, resulting in multiple mobi-

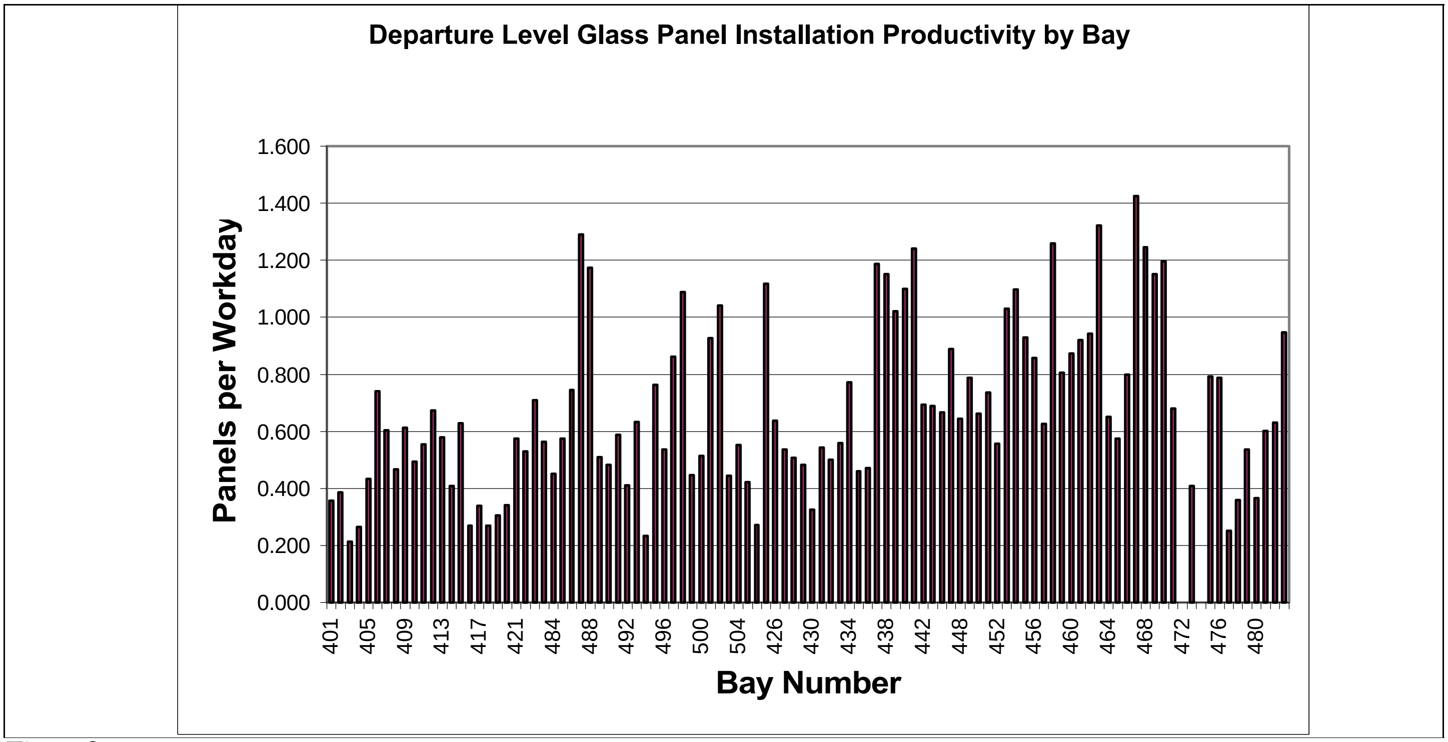

Figure 3

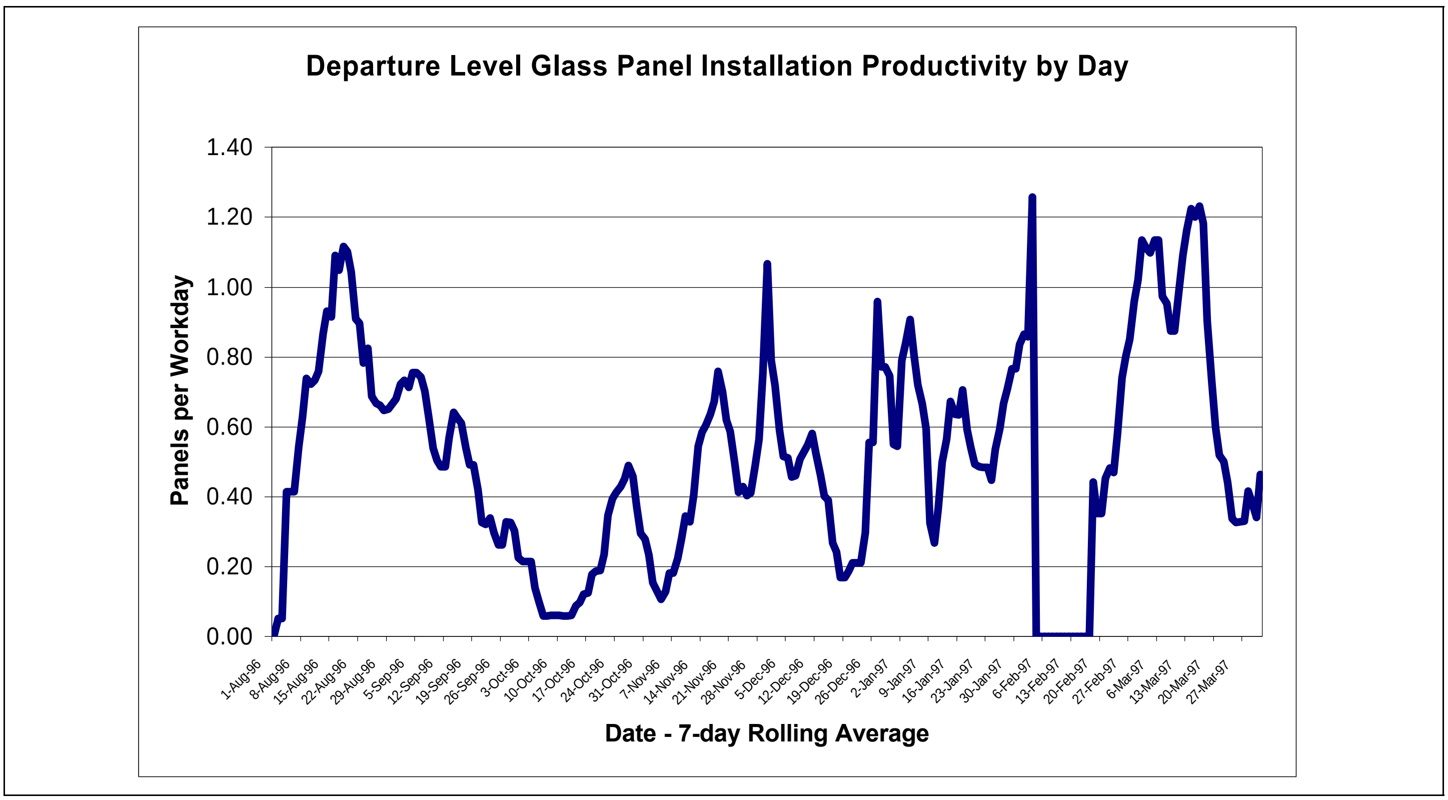

Figure 4

lizations, frequent returns to a specific bay, and the inability to work consistently in a single area. Figure 4 depicts the data viewed by number of panels installed by date.

The data depicted in figure 4 were averaged, or "smoothed," over a seven-day period to address production reporting vagaries. For example, the analysis revealed that, although infrequent, there were instances in which glass panels were installed on day-one but only secured in place by temporary clamps. These panels were not listed as "installed" until the following day, when final clamps were inserted. Thus, on day-one only a few panels were completed, while on day-two numerous glass panels were "installed." A rolling seven-day productivity average in panels per workday was, therefore, a more meaningful representation of the actual performance of the work.

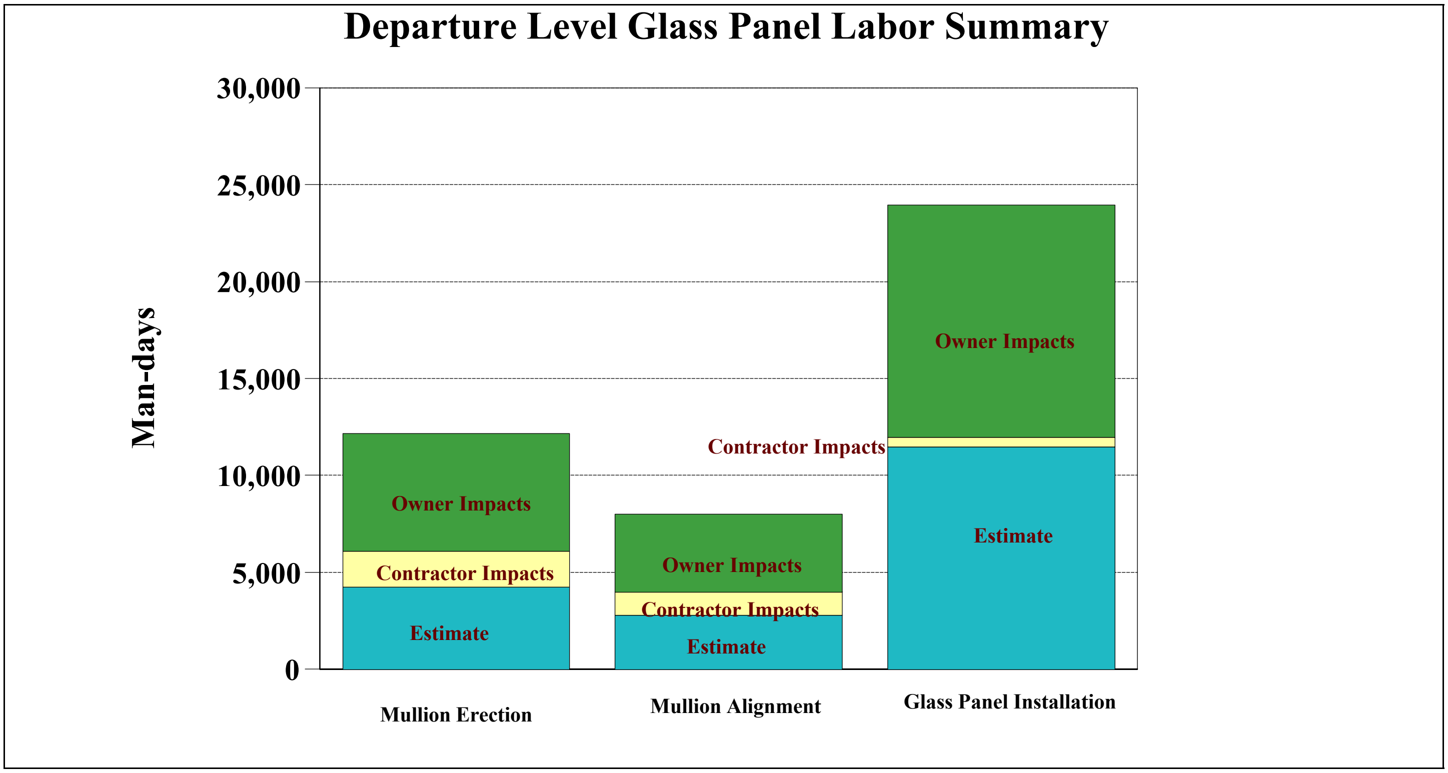

Figure 5

Notwithstanding the accuracy of the depicted productivities, two aspects of the above charts require further explanation. First, there is relatively high initial productivity in late August 1996, when low learning-curve productivity might be reasonably expected. This anomaly was the result of the premature reporting of the "installation" of the glass panels by the field supervisors. At this early period of performance, supervisors were only starting to understand some of the design defects they needed to overcome, and their resulting implications on task completion. The supervisors were reporting as "installed" glass panels that had not, in fact, been finally aligned or clamped into place. Second, and as a corollary, low productivity in October 1996 was a direct consequence of the initial high productivity reporting. During this time, a significant amount of labor was expended completing the overstated work that had earlier and erroneously been recorded as "installed."

From these studies, the authors concluded that the actual DLE, or measured mile, for this project was 1.1 panels per workday, as achieved in mid-March 1997, at bays 437 through 440, and 467 through 470.

The authors also reviewed the initially planned workday estimate in order to ascertain and confirm that contractor-caused problems were included within the DLE calculations. Figure 5 summarizes that study.

STEP FIVE: TURNING THE DLE CALCULATIONS INTO DAMAGES

The arbitrators in this matter required that the damages be date, cause and location specific. The authors believe that such an uncompromising requirement, absent either an understanding of the validity or thoroughness of the available data, might ultimately add a false sense of detail and accuracy to calculations. This level of detail is not always supported by the DLE methodology. Stated differently, DLE calculations in general, and the glass panel installation calculations specifically, were the best approximation of the actual productivities achievable as measured at the task level. The smaller the data segment or unit utilized in the calculation, the less precise the resulting calculation became. Nevertheless, the arbitration panel required that damage calculations be very detailed. The authors, therefore, converted the DLE into a calculation of what the workforce should have been on a day-by-bay basis by using the DLE productivity. In response to that demand, the following calculations were performed.

1. Glass panels installed—based on the actual daily field counts of the contractor as confirmed by the owner's inspections, inaccurate data excluded.
2. Labor workdays—known for each day, allocated each day by number of glass panels installed. Inaccurate data excluded.
3. Productivity—number of glass panels installed by day and bay divided by the labor workdays for that day and bay.
4. Direct labor efficiency workdays—number of glass panels installed by day and by bay multiplied by the DLE productivity.
5. Impact workdays—actual labor workdays minus DLE workdays.
6. Impact workdays adjusted for sample size—due to adjustments made in the early steps associated with misreporting of data and other apparent data inaccuracies, the DLE was calculated using only a portion of the actual labor expended doing the work. This calculation applies the DLE calculation to all the labor for this task.
7. Total labor cost for task—adjusted impact workdays multiplied by workday labor rate.

Calculation 6 requires further explanation. Through the initial steps, deficiencies in the underlying data required that certain portions of that data be excluded (corner bays, as previously discussed). The overall workdays expended performing this work, including the missing days in February 1997, were known in the aggregate. Therefore, the DLE calculated productivities were applied to all the labor charged to the task, not just the smaller sample included in the DLE study.

Calculation 7 reduced a complicated set of labor cost calculations into a single statement. In reality, the authors performed extensive studies to arrive at the average workday cost. First, the actual payment to the workers had to be calculated—made more difficult by the differences between worker pay rates depending upon their nationality. Further, Hong Kong labor practices often required the use of labor brokers and corresponding complications in tracking payments.

Even after average daily pay was determined, including overtime, certain overhead labor workers (who were identified as "scaffold" or "shop") had to be included. These workers were generally the material handlers, equipment operators, safety officers, quality control inspectors, and others who worked on one or more tasks, and therefore had to be allocated to multiple DLEs. The authors reduced these labor workdays to actual costs and allocated them as a surcharge to each workday hour worked.

Finally, the delays, impacts, and disruptions actually experienced caused an increase in the overall onsite project overhead. Since all work was performed on an island, and all workers had to be transported to and from the island or be provided housing on the island, there were substantial additional costs associated with both transportation and housing. Additional supervision was also required, as well as a full panoply of support services. These site overhead charges were incurred on all aspects of the project and were allocated pro rata to the daily labor cost in order to facilitate their inclusion in the labor rate.

The quality, quantity, and accuracy of the contemporaneous project data, along with contract and settlement venue considerations, ultimately determine the selected methodology (or methodologies) viable for use in performing analysis. On the Hong Kong airport project, the authors initially determined that the available project documents supported a DLE-type approach, which led to approximately 175,000 separate database calculations to support a single DLE analysis. Considering all the DLEs performed, the interim drafts, and the final arbitrators' report, the authors estimate that millions of such arithmetic calculations were made in reaching the cost calculations used in the settlement. This type of effort would not have been possible without computerized databases and their advanced capability to organize, collate, and calculate. Therefore, in today's construction industry, the increased size of the project, and hence the increased size of the databases, aid in performing accurate analysis.

More importantly, the authors believe that demonstrated labor efficiency calculations can be made even where the underlying information has missing, incomplete, or inconsistent data. Judicious exclusion of suspect data points, with candid explanations of the methods chosen to exclude and "smooth" the remaining data, produces DLE calculations that are more accurate and complete than other calculation methodologies that attempt to obscure defective or suspect data.

In sum, the ability to look at virtually all components of a project as individual, discernable DLEs is a comprehensive and accurate method for calculating labor inefficiencies and their attendant loss of productivity costs. This methodology is preferred over use of aggregated DLEs or total cost claims.

REFERENCES

1. McCally, B.M. **Cost Engineering** (November 1999).
2. Zink,D.A. **Cost Engineering** (April 1986).

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