APPLICATION OF TOLERANCE ANALYSIS AND ALLOCATION IN WORK STRUCTURING: PARTITION WALL CASE

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ABSTRACT

Geometric tolerance as a source of variability is often ignored in project design and control research and practice. Certain best practices to buffer AEC systems from this variability are established through 'received traditions.' To describe the nature of this variability, basic tolerance terminology is introduced as applicable to a case study. Tolerance analysis and allocation techniques are herein applied to a very simple AEC system, a drywall partition wall with an electrical outlet. A mapping system, combining aspects of tolerance analysis tools and process mapping, reveals strategies for improved tolerance allocation that often results in the design of alternative work structures. Alternative work structures not only meet the system geometric tolerance constraints but they also attempt to remove waste from the system. The methodology for mapping and analysis are shown to mitigate geometric variations through product and process configuration. Speculation is that the same methodology is adaptable to design systems that are robust to any form of variability impacting the system.

KEY WORDS

Tolerance, constructability, work structuring, lean construction, mapping

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INTRODUCTION

Designers and contractors may feel that tolerances do not have a significant impact on project performance for the majority of their work. This feeling appears to have prevailed in at least 30 years (Birkeland et al. 1971, Walsh et al. 2001, Milberg et al. 2003). Tolerances are not viewed as a problem because they are seldom measured; the causes and effects of tolerance problems are not well understood and they often remain unseen. In addition, the steps and strategies employed by contractors to deal with geometric tolerances are often tacit knowledge. A goal of the authors' ongoing research is to make this knowledge explicit.

The focus in this paper is on geometric tolerances. Geometric tolerances are means for describing the acceptable range of variation in geometry from a nominal or reference geometry. Managing such tolerances is key to achieving performance of engineered systems, such as the systems built in the course of construction.

A residential contractor estimated that the costs of remodeling amount to 1.5 times the costs of new construction. This factor does not include the cost of demolition or contingency for unknown conditions; thus, it assumes that the product scope is the same. Asking why the estimates for remodeling are higher, the importance of geometric tolerances becomes clearer. Remodeling may take significantly more time because each piece of the construction may have to be measured and custom cut to account for the existing structure being out of square, bowed, etc. The factor also includes contingency for restrictions on access (bringing resources to the workface) and on process sequence due to the existing structure. Clearly, variations in geometry can have a significant effect on the duration and cost of construction.

In all areas of construction, activities and systems have been created to deal with geometric tolerances. Some examples are: reaming steel holes, shimming, using trim, caulking, grouting, using spacers, starting tiling from the center, and leveling equipment and appliances with adjustable feet. These activities and systems become incorporated into trade knowledge and practice as 'received traditions' (Schmenner 1993 p. 379) developed through the long history of architecture, engineering and construction (AEC) without investigating better methods.

Materials and techniques currently in use for dealing with tolerances already may be the most efficient. However, less widely adopted materials and tools for fabrication and measurement are becoming less costly, and new ones are being developed. Their use may reduce or even eliminate the need for some of the existing activities and systems. For example, the use of computer numerically controlled (CNC) machines to fabricate structural steel members is reducing the percentage of connections requiring reaming and thus the duration of work on site. New practices may affect not only a single activity, but the entire work structure. Work structures encompass the design and arrangement of products, activities, supply chains, control practices, organization, and participants within a project system. Alternative work structures with different allocations of tolerances among the components and activities can improve project performance overall (Ballard et al. 2001).

In manufacturing, tools and techniques for geometric tolerance management have been successful in reducing the cost and schedule for a particular operation and in generating designs or activity sequences that are more robust to geometric variations. Robustness is the resistance of the system to changes in performance due to manufacturing or under unplanned conditions (Taguchi et al. 1999). Although some feel that the available tools are still too limited for widespread application to large assemblies (Trabelsi et al. 2000) like construction, there is much to learn from tolerance management techniques.

This paper presents alternative work structures for the simple case of a drywall partition wall with an electrical box. A mapping system combining aspects of several tolerance management tools shows the tolerance loops associated with these alternatives. Comparing the maps reveals strategies for process sequencing and other work structuring design decisions that result in systems that are more robust to geometric tolerances. Ongoing research is investigating how to use these strategies to design work structures that are robust not only to geometric variation but also to other forms of AEC project variation.

PARTITION WALL PROBLEM

An example will illustrate the impact tolerance may have, within alternative work structures, on the installation of a standard stud partition wall containing an electrical box for a switch or outlet. Figures 1 and 2 show the relationships between the wall's wood framing system (shown in brown), the electrical box (shown in grey) and the drywall (shown in light blue). The critical dimension (CD) and tolerance of interest is the gap between the edges of the hole cut in the drywall and the electrical box. The hole should be cut large enough to accommodate the box penetrating through the drywall (as well as any variations in the box and drywall positions during installation). In addition, the hole must be small enough to be covered by the outlet plate without showing a hole in the finished wall. The problem is meeting both the upper and lower limits for the size of the hole. The need for penetration and coverage are frequently sources of tolerance problems.

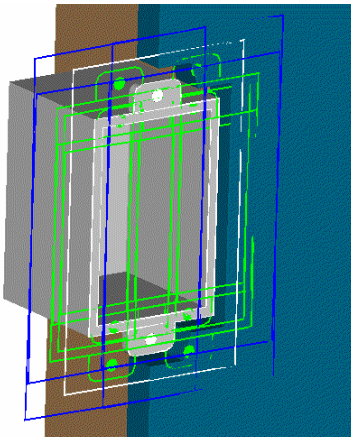

Figure 1: Drywall, Stud, Box and Plate Outline with Variations in Box and Plate Location and Orientation

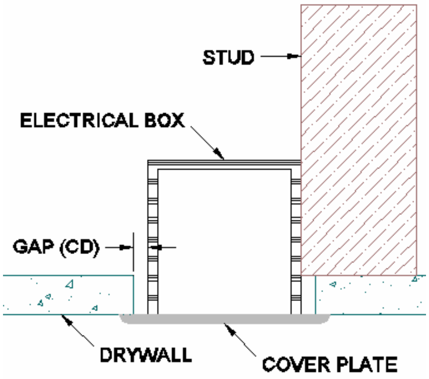

Figure 2: Section View, Looking Down, Taken at the Center of the Box

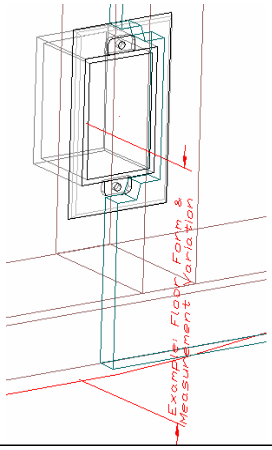

Figure 3: Impact of Floor (Datum) Tolerance on Vertical Location Tolerance of the Box

Figure 1 shows the plate's (in dark blue, darker outlines) and the box' (in green, lighter outlines) potential variations in location and orientation from the location of the hole in the drywall according to the design drawing. The white outline is the reference or plan position of the box and plate. In some conditions, the green box outlines overlap with the drywall, which indicates a penetration interference; in other conditions, the blue plate outlines fail to cover the hole in the drywall, which indicates that a gap will remain.

TOLERANCE TERMINOLOGY

Manufacturing researchers have developed a taxonomy for geometric tolerances. Some of their terminology is presented here for better understanding of the example. Major types of manufacturing tolerances are (1) form-, (2) orientation-, and (3) location tolerances (Henzold 1995). Figure 4 illustrates these tolerances and their relationship. Each tolerance as shown refers to the thick wavy line in the center. The reference or theoretical geometry for that line is shown by the dashed-dot line (— • —). The reference line is designated by a nominal location or distance from the datum. A datum is a reference feature or geometry from which other features or geometries are defined. A datum is represented as a perfect feature or geometry for the purposes of defining the nominal geometry and tolerances of other features or geometries when in fact, it too has some variation as shown in figure 4. Many rules exist regarding the specification of a datum and how variations in a datum are treated, but these are outside of the scope of this paper.

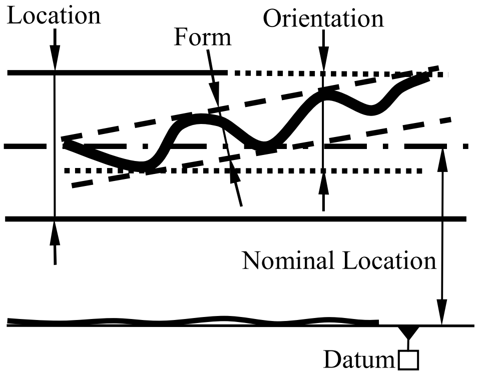

Figure 4: Standard Geometric Tolerances (Henzold 1995)

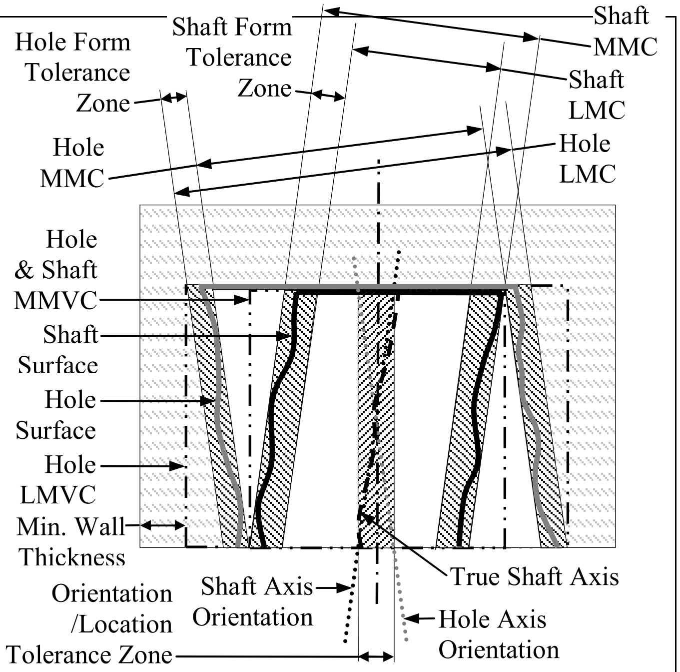

Figure 5: Maximal and Least Material Virtual Conditions (Henzold 1995)

The form tolerance, shown by the dashed line (– – –), shows the limits in the variation of the line’s shape. The orientation tolerance, shown by the dotted line (• • •), shows the limits of the line along its entire length due to the variation in the line’s overall orientation. The location tolerance, shown with solid line (——), shows the limits of the line along its entire length due to variation of any part of the line from its nominal location. Thus, the location tolerance includes orientation tolerance and the orientation tolerance includes form tolerance. All three however are required to provide detailed information about the geometry's deviation from its nominal geometry. However, form-, orientation-, and location tolerances only have this relationship when they apply to the same feature or geometry. Location-, orientation-, and form tolerances may apply to different features of the same part resulting in a cumulative rather than a nested effect for a part feature. Figure 5 shows an example where the orientation tolerance applies to a shaft axis while the form tolerance applies to the shaft surface. The impact of the shaft and hole surface deviation is cumulative.

Three functional tolerances (Henzold 1995) are useful in describing the drywall example. They are introduced in concept but a full explanation is outside the scope of this paper. First, the maximal material virtual condition (MMVC) is often applied to ensure the mating relationship between a shaft and a hole. Figure 5 is a cross section through a part with a hole whose surface is shown by the thick, solid, grey line. The thick, solid, black line illustrates the surface of a shaft inserted into the hole. The hatched areas show the form tolerance of the hole and shaft surface, and the orientation/location tolerance of the hole and shaft axes. The location- and orientation tolerances for the hole and shaft axes are the same in figure 5. The MMVC, shown by a dash-dot line (— • —), defines the boundary that neither the hole nor the shaft may exceed to ensure mating when they are both at their maximum material condition (MMC) for surface form variation and maximum axis orientation/location variation. The MMC for the hole is the condition where the hole is the smallest (the part containing the hole has the most material). The MMC for the shaft is the condition where the shaft is the largest (has the most material). In Figure 5, both the hole and the shaft surfaces are shown near their MMC limits and their axes are shown at their maximum orientation variation limits.

Second, the least material virtual condition (LMVC) often applies to making a hole in a piece of material. The LMVC for the part containing the hole is also shown by a dash-dot line. The part has a minimum wall thickness requirement. The LMVC is the boundary that the hole may not exceed to ensure the minimum wall thickness when the hole is at its least material condition (LMC) for surface form variation and maximum axis orientation and location variation. The LMC is the condition where the hole is at its largest due to the surface form variation (the part has the least material). The exterior surface of the part is assumed to be in its nominal form.

Third, positional tolerances are similar to location tolerances. A positional tolerance zone is symmetric about its defined location. Positional tolerances are often used to represent the relationship between a set of features such as a pattern of holes. The positional tolerance defines the theoretical exact location of a point, line, or plane that is the reference geometry for a feature similar to the nominal value used for a location tolerance. The tolerance zone forms a symmetrical envelope, which the combined form-, orientation-, and location tolerances of the feature may not exceed. For example, the orientation- and location tolerance zone in figure 5 could represent a cylindrical positional tolerance zone for the shaft axis specified at the center of the hole and shaft. This positional tolerance means that the true axis of the shaft including its form-, orientation-, and location deviations must be contained within the cylindrical tolerance zone. If the hatched zone in the center were a positional tolerance zone, the shaft shown in figure 5 would be unacceptable. The true axis, which reflects the form variation of the surface, exceeds the zone at the end of the hole.

In the case of all the functional tolerances, the manufacturing tolerances are flexible. For example, in figure 5, the form deviation of the hole surface does not reach the LMC tolerance limit. This means that the orientation deviation could exceed the location and orientation tolerance limits shown and still meet the LMVC requirement but not the MMVC. Functional tolerances by themselves do not dictate explicit limits or relative distributions for the individual manufacturing feature tolerances. Instead, they define an envelope that shows the maximum allowable impact for the combined deviations of all the manufacturing features.

TERMINOLOGY APPLIED TO THE PARTITION WALL PROBLEM

Refer again to figures 1 and 2. The lower limit for the size of the hole in the drywall is a function of the form-, orientation-, and location tolerances of the box, drywall, and drywall hole. For example, assume the tolerances allow the box center's horizontal location to be 13 mm (½") off its plan position and centerline's orientation to be rotated 1 degree from its plan orientation. Assume the form tolerances for the box, the location- and orientation tolerances for the drywall, and the layout of the drywall hole are negligible. Also, assume the hole is cut in the drywall based on the plan. The width of the hole will need to be 28 mm (1-1/16") larger than the box width (13 mm (1/2") for the location and 1 mm (1/32") for the orientation tolerances on both sides) plus an allowance for the form tolerances associated with cutting the width of the hole. This is the MMVC because it represents the limit for the most material the component features can have. The limit describes the maximum space the drywall (and the box) may have and the minimum size the hole must be to meet the mating condition. Mating means that the box sits within, that it successfully penetrates the hole given its maximum variations.

The upper limit for the size of the hole is a function of the tolerances affecting the lower limit plus the form tolerances of the cover plate. The form tolerances for the cover plate are negligible because its manufacturing tolerances are small. Cover plates are 19 mm (¾") wider than electrical boxes, 9.5 mm (3/8") on each side. Therefore, for the plate to cover the hole, twice the tolerances for the relative location and orientation of the box and the drywall (each side) plus the tolerances associated with cutting the width of the hole cannot exceed 19 mm (¾"). This limit is the LMVC because it represents the least material the component features can have. The limit describes the least material the drywall (and plate) can have and the maximum size the hole can be to ensure coverage.

PRODUCT TOLERANCES AND PROCESS CAPABILITIES

Product geometric tolerances provide a detailed description of the range of possible states that can be expected and accepted for a component product. The variations are the result of the product's manufacturing, storage, transportation, and installation processes and the environment or system in which the product operates. The sources for variations are broken down according to the 6M's: Material, Machine, Manufacturer, Method, Measurement, and Maintenance (e.g., Schmenner 1993). The ability to control variations in the output of a particular process is referred to as the process capability. If the process capability does not meet the specified tolerance, the outputs can be inspected and those exceeding the tolerances rejected. The next sections discuss a few variations and sources of variations for the major elements of the partition wall, the wall frame, the box, and the drywall for this example.

WALL FRAMING TOLERANCES

A typical wood-frame wall installation sequence starts with framing the wall with 2X4s as the headers, floor plates, and studs at 40.6 cm (16”) on-center and plumb. The header, floor plate, and studs all have a form tolerance and may be warped or twisted as a function of their manufacturing, transportation, storage, and inspection processes and conditions. The framing components may initially have tight tolerances on form when milled. Sources of milling variation may include: material feed rate; saw blade speed; mill environment; flexibility of the saw bearings; flexibility of the saw blade; sharpness of the saw blade; structure of the wood grain; form of the guide surface; the form of the wood’s surface against the guide surface and more. Yet, uneven loading or changing moisture and temperature given the natural variations in the wood can result in significant form changes during transportation and storage. The header and floor plate variations, however, have little impact on the critical dimension because they are not used for box attachment or position measurement. Only stud variations are considered here. Thus, tradesmen will often inspect studs visually for straightness before selecting them for use to minimize variations. Additional form variation may occur during installation. Under conditions where the floor and ceiling are installed before the wall, the stud may bow if cut too long lengthwise and forced into position. Variations in the thickness of the 2X4s used as header and floor plate can add to this bowing.

For this type of wall, the studs typically have a positional tolerance both for their layout and erection. The positional tolerance is specified in the floor plane and limits the acceptable form-, orientation-, and location variations in the actual centerline of the stud from floor to ceiling. Positional tolerances are specified in the plane perpendicular to the desired tolerance zone. The positional tolerance can depend highly on how the layout dimensioning on the plans is interpreted and how the layout is then measured (Birkeland et al. 1971). The number of datum used to mark out the wall plane and the location of each stud changes how and how much error accumulates. The datum can be a theoretical geometry such as a point, line, edge, plane, etc. but in practice, usually it is any available feature of a component such as the bottom edge of a nearby existing wall. The datum feature is then treated as the theoretical exact geometry (a straight and level line in this case, even though it has variations similar to the datum in Figure 4). This existing edge, acting as the datum, is used here to determine the stud centerlines in the partition wall. However, because the datum can have errors (variations from the theoretical geometry), a relative location to the reference feature (the nearby wall’s wavy bottom edge) is what is actually provided. In addition, there is the measuring error for the layout to consider. The positional tolerance can also depend highly on the assembly process, for example, where stud orientation is determined with a level. Personal experience indicates that variations in the center of the stud at any point along its length do not typically exceed 13 mm (1/2”) without being modified in process.

ELECTRICAL BOX TOLERANCES

Once the frame is installed, the electrician starts measuring from the floor to the specified height and then nails the electrical box to the stud. The box is assumed to have a negligible form tolerance from its manufacturing, however, it has an orientation tolerance in terms of how square it is with the wall plane, and with the floor- or ceiling plane. The box has a location tolerance for the horizontal- and vertical location of its center on the wall as well as for its reveal from the wall plane, which should equal the drywall thickness. The location- and orientation tolerances are functions of the on-site assembly by the electrician, the tolerances of the stud used to secure the box and as a datum for the wall plane, and the form of the floor used as a datum for the floor plane. Figure 3 illustrates how the floor elevation deviations, in residential construction observed to be on the order of 13 mm (1/2”) (Walsh et al. 2001), may impact the vertical location of the box center.

DRYWALL TOLERANCES

Next, installers hang the drywall from one end, chosen or designated in the plans as the starting/datum end, until they reach a piece to be penetrated by an electrical box. Drywall is assumed to have a negligible form tolerance from its manufacturing. Drywall openings to accommodate windows or doors can be cut from the plans but more typically are cut from field measurements taken prior to hanging. Drywall has location- and orientation tolerances associated with onsite assembly. Care is taken to keep each piece’s centerline plumb and its edge close to the adjacent piece. A small space may be left between adjacent pieces of drywall, the ceiling, floor, doors, and windows to accommodate form-, orientation-, and location tolerances from cutting and hanging. These spaces, as well as dimples from fasteners used to secure drywall to studs, are filled by joint compound or covered by trim molding.

TOLERANCE PROBLEM

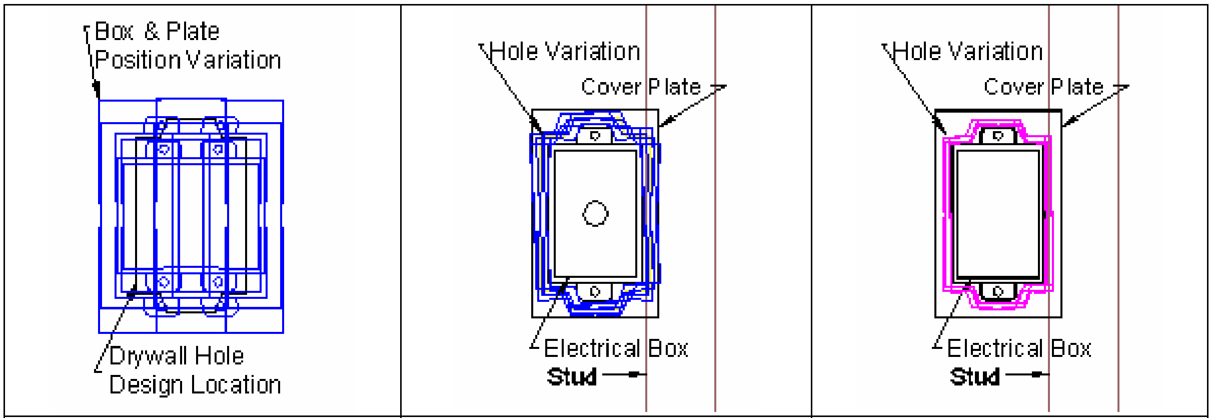

Figure 6-A: Box and Plate Location and Orientation Variation with Fixed Hole

Figure 6-B: Hole Location and Orientation Variation from Installed Box Measurement

Figure 6-C: Drywall Hole Position Based on Installed Box Impression

Figure 6: Relationship between Drywall Hole and Electrical Box Locations and Orientations Given Alternative Processes for Marking the Hole

All the tolerances for the wall frame, box, and drywall combined create uncertainty in the position of the drywall relative to the box. This uncertainty is too large for the installer to cut a hole in the drywall based on the plans while ensuring proper mating (Figure 6-A). Instead, the drywall installer can measure two dimensions to the center or edge of the box from the floor and adjacent piece of drywall (USG 2003) and map this location onto the drywall. The installer then cuts out an opening larger than the box using a drywall saw and sets the piece in place. Some variations will occur due to measurement, layout, hole cutting, and drywall installation (Figure 6-B). Alternatively, the installer can put the drywall into its position before cutting the hole and press it against the box to create an impression as a means to mark the cut for the box. The installer then moves the drywall down, cuts a hole larger than the impression (with some variation) and replaces the drywall (with some variation from its original position) (Figure 6-C) (Reader's Digest 1991).

Alternatives 6-B and 6-C take into account field dimensions. Both require time to measure or create the impression, though that time is minimal. Alternative 6-C also requires lifting the drywall twice. This example does not present a big problem in the industry, but it was chosen because of its simplicity and expected familiarity to readers, allowing for focus on the details. Despite its limited scope, improved practices could still add up, assuming for example an electrical box in 30% out of 5,000 sheets of drywall in a building.

TOLERANCE ALLOCATIONS

TOLERANCE LOOPS

The critical dimension (CD) is the gap between the box and the edges of the drywall hole. Figures 6-A, 6-B, and 6-C depict the results of 3 tolerance loops with similar elements. Figure 7 shows the loop for the sequence represented in figure 6-A. Geometric variations begin with the tolerances in the wall layout starting at the wall reference datum. Only variations associated with the positional tolerance of the stud layout impact the CD. Other layout tolerances impact other functions of the wall related to the rest of the structure. Next in the path are the orientation- and location tolerances for the studs' central axis resulting from the erection of the studs. The studs' form tolerance resulting from the stud procurement and shaping are part of the stud datum. Next are the orientation- and location tolerances for the box' central axis, resulting from its erection.

The three sequences share the path described above (the top path inside the dashed box in figure 7). In figure 7 this path is closed by another path (the bottom path inside the dashed box) that also starts from the wall reference datum to form the loop. The bottom path begins with the orientation- and location tolerances of the layout lines for the edges of the hole in the drywall. The path goes through the form-, orientation-, and location tolerances for the hole's edges, resulting from the hole cutting. Next comes the location and orientation tolerance for the erection of the drywall's central axis, for the piece in which the hole is contained. Finally, the paths are connected at the CD by the LMVC and MMVC tolerances between the box plate or box, and the edges of the drywall hole, respectively.

The main loops in figure 8 are smaller than those in figure 7. In figure 8, the floor plate form tolerance contributes to the hole layout location tolerance for 6-B, but not for 6-C. The datum transfer, measuring and laying out the hole for 6-B, has a larger tolerance than making the hole impression for 6-C. All these factors help to explain the difference in cumulative tolerance at the critical dimension in figure 6. The observation is: the more datum, the more tolerance-contributing activities; and the larger each contributing tolerance in the main loop, the greater the deviation at the CD. Thus, reducing the individual contributing tolerances is not the only way to mitigate cumulative tolerances. Another way is reducing the number of datum and tolerance-contributing activities within the main loop. This highlights the importance of parameter design and datum selection as was identified in manufacturing tolerance management techniques for robust design (Houten et al. 1999, Zhang 1997).

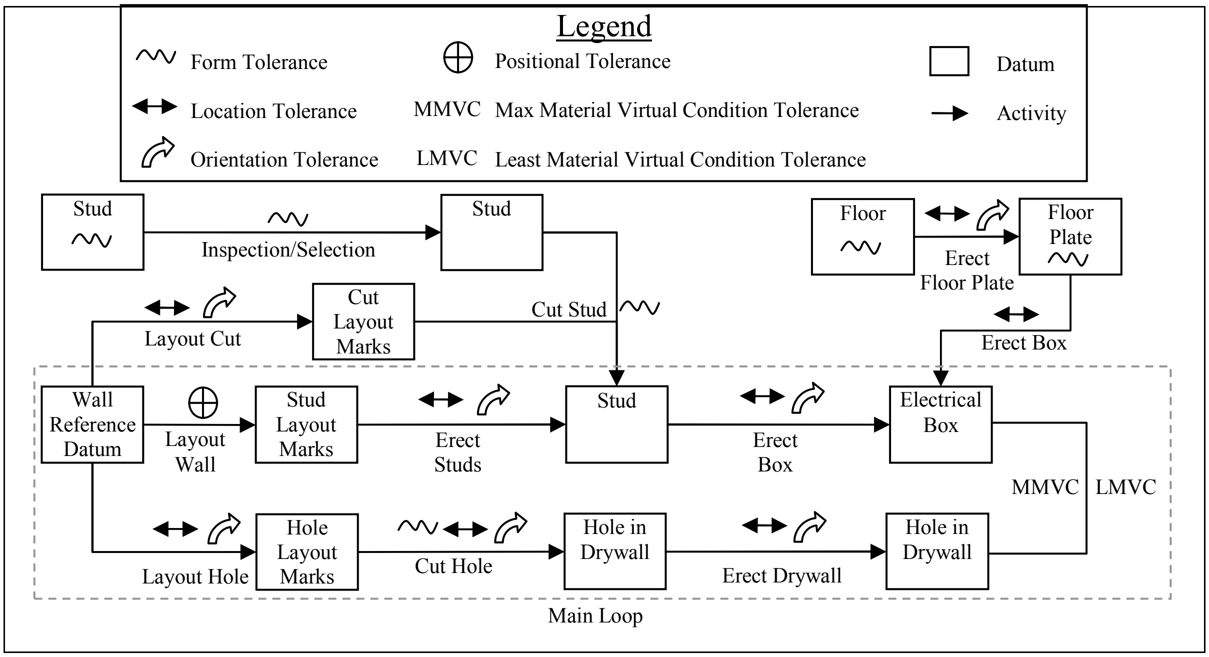

Figure 7: Tolerance Loop for Sequence shown in Figure 6-A

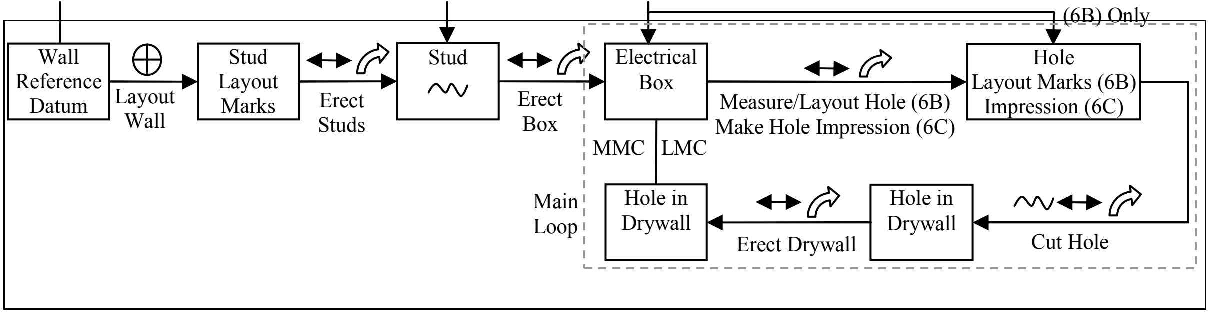

Figure 8: Tolerance Loop for Figures 6-B and 6-C

MAPPING SYSTEM

The maps in figures 7 and 8 combine elements of value stream mapping, tolerance symbols, tolerance analysis tables, and tolerance network mapping. Tolerance network maps have various component features for the nodes connected by lines with symbols representing the tolerance relationship between the features (Tsai and Cutkosky 1997). For example, the relationship between the left and right surfaces of the box might have a parallelism tolerance defining their geometry relationship. Tolerance networks provide a means to visually represent all the loops and their relationships. Tolerance analysis tables show the relative contribution of each feature tolerance in a loop to a CD as well as the CD sensitivity to further variation in each feature (Houten et al. 1999, Zhang 1997). However, both tolerance networks and analysis tables do not explicitly represent information about fabrication and assembly processes. Instead, tolerances are associated with part features that are sometimes based on intended or assumed—but often unidentified—processes. Also, a tolerance analysis table can be produced only when the CD has been identified. The selection of the CD depends on the function of the system at all stages in the life-cycle, including functions associated with meeting fabrication and assembly process constraints created by the process sequence not yet identified.

The maps show process information on the lines connecting the nodes, and represent the tolerances they create in the components as originating in the process. This representation allows for clear identification of a CD based on manufacturing and assembly constraints as well as final functions. The nodes used are mostly components in this case, for simplicity. With more space, decomposing the nodes into features would be more specific. The nodes shown were chosen because they are used by the process following the node as a datum, a reference for the process of shaping or positioning a component or feature. Tolerances inherent to the datum component or feature are represented in the node to ensure that they are not overlooked. Two features of the tolerance analysis tables, the individual tolerance magnitudes and CD sensitivities, are not shown in the maps but could be easily added. Magnitudes could be shown with colors and sensitivity represented by separate symbols for each direction of variation.

The maps help to identify and evaluate the feature chosen as the datum for a process. Efforts should be made to reduce the number of datum used for a series of processes. Preference would be to use a select few datum for many activities, making a cluster of small loops around those datum. Though not explained in detail here, other principles emerge from the mapping evaluation. The CD should be chosen as the interface with the most flexibility to absorb variation if this is possible given the process constraints. Also, process sequences would preferably start at the most restricted datum. 'Most restricted' means that the datum is shared by most loops, has a very tight tolerance, or is a CD for another loop. Process sequences should then progress along multiple paths that merge at the critical dimensions. This maximizes the simultaneity of activities with no impact on the CD.

RELATED WORK

Tolerance management is a part of AEC research. Constructability literature includes geometric tolerances as a source of constructability problems (CII 1993) and 'tolerance' is a keyword currently used by the ASCE Constructability committee. However, identifying strategies to mitigate tolerance problems does not appear to be part of ongoing constructability research.

The Open Building Movement's (OBM) (Hartog 1997) strategy for modularization successfully mitigates many types of tolerance problems including those related to penetration and coverage. Their success comes from extensive analysis of variety (variation) of necessary interfaces found in residential construction. This analysis led to the development of simple standard interfaces that accommodate the variety. Necessary interfaces are determined by several factors such as differences in function, environment, and market life. Much can be learned from how the OBM system deals with tolerances but their findings are limited. OBM is focused on residential construction. Interface analysis and design would have to be carried out for other types of construction, and they may have to be specific for the interfaces to be efficient. Finally, the identification, analysis and design of the necessary interfaces, interface variety, and standard interfaces require extensive time. The goal of this research is to generate more general strategies for tolerance mitigation that can be evaluated within a reasonable time on any type of project as the project is initiated.

CONCLUSIONS

The partition wall case presented here illustrates several points. First, geometric tolerances related to products and processes in AEC systems can have a significant impact on the design, production, and outcome of the system. Failure to acknowledge and account for tolerance-related variations in design can have negatively impact the goals of the project, making the system both un-reliable and not robust to material and process variation (Milberg et al. 2002). Though not elaborated on in this paper, these negative impacts may ripple through the rest of the project (Milberg et al. 2003). Second, it is possible to map the source and propagation of geometric variation through the system. Maps have illustrated that tolerances can be mitigated through work structuring, in addition to reducing the magnitude of individual tolerances.

The maps as presented allow for comparison of work structures in terms of robustness to geometric tolerances. They also help to visualize improvements in robustness by reducing the size of the tolerance loops. One strategy identified is to break systems into the smallest loops possible. However, caution is required as resources participate in multiple loops within the system. More loops tend to lead to more complex interdependencies among resources. This could be seen if all tolerance paths were represented for the whole building in which the example wall is a part. An alternative strategy might be to break the system into the largest consistent loops possible with the least connections between loops. A “consistent” loop is one where all the contributing tolerances form the worst probable case and all the system constraints are still met. Formalizing this strategy and balancing tolerance management with other project goals is the subject of ongoing research. Strategies being investigated include better datum selection, parameter design, changing the location or direction of variation through interface or process sequence configuration, variation reduction through process selection, and adding excess capacity.

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