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TRACKING DESIGN DEVELOPMENT THROUGH DECOMPOSING SKETCHING PROCESSES

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ABSTRACT:

We conducted a protocol study of the architectural sketching process. We decompose the process into process flows to explore the extent to which it expresses concept development in schematic and refined design phases. We track the development of design concepts in these phases by following the process flows of individual sketched strokes. We argue that each stroke drawn by the designer reveals a probability of an embedded concept, and that this concept is either promoted and propagated throughout the design phases, or blocked while designing. We expand the notion of lateral and vertical transformation in design by introducing a set of processes described as cross propagation, lateral promotion and vertical promotion.

1. INTRODUCTION

Architects often use sketches in the design process (Do, 2005; Goldschmidt, 1994; Lawson, 1990; Suwa and Tversky, 1997). Sketching activities play a vital role as a seamless practice in architectural design processes. Freehand sketching is still considered by architectural firms as the preferred method to externalize design concepts. Being suitable for the ill-structured nature of design problems, architects can produce, modify, refine and assess design ideas effortlessly with freehand sketches.

Conventional freehand sketching with tracing paper and pencil is still recognized as an effective medium of expressing design concepts. Lawson (1994) describes that designers "find it hard to think without a pencil in their hand". Ullman et al. (1990) that the sketching actions of ‘marks-on-paper contain different types of information’. We propose that design concepts could be tracked through analyzing sketched strokes in schematic and refined design phases.

Various methods exist for studying the role of sketching in design. According to Ericsson and Simon (1984), think-aloud protocols are often used to study problem-solving activity. Analysis of verbal and graphic protocol attempts to account for correlations between drawing and design thinking. Suwa and Tversky (1996) used retrospective reports of design sessions to study designers’ perceptual processes. Porter (1988) carried out speculative accounts of design processes as ‘thought-experiments’ to account for the underlying logic of designing. We conduct a protocol study to observe the detailed activities of sketching over time, and how they can infer about design development. From the results of the detailed protocol study, we decompose the sketching process into a group of process flows in order to track concept development.

2. CONCEPT DEVELOPMENT AS CAPTURED IN SKETCHING

2. 1. EMBEDDED CONCEPTS IN SKETCHES

Sketching has been viewed as containing the seeds of ideas (Cheng and Lane-Cummings, 2004). They argue that the process of germination of those seeds is obscured in final documents, as not all the incremental updates and iterations of design concepts are represented in the final static stage of the sketch. According to Do et al. (2000), the roles that researchers assign to sketching

in design include generating concepts, externalizing problems, organizing cognitive activity, and facilitating problem solving, perception and translation of ideas.

According to Chastain et al. (2002), sketches are “semantically open”. They propose that “a design task is abstract; typically conceptual; it is more concerned with exploration than with describing a solution and implies more than it defines”. Goldschmidt (1991) views sketching as an ‘oscillation of arguments’ that brings about a gradual transformation of images. Schön (1983) argues that designers first ‘see’, then ‘move’ design objects in a continuous process of reflection in action. Similarly, Suwa and Tversky (1997) argue that designers “see unanticipated relations and features that suggest ways to refine and revise ideas” as they inspect sketches.

According to the previous views, we see the design sketch as an ever-growing pool of embedded design concepts, where each individual stroke represents a potential seed for a new design concept. In this pool of potential concepts, continuous growth, transfer and development of strokes, and consequently design concepts, occurs along time.

2. 2. CONCEPTUAL TRANSFORMATIONS IN DESIGN

Goel (1995) describes two main types of transformations that occur during conceptual development in the design process; lateral and vertical transformation. Lateral transformation is said to be “…one where movement is from one idea to a slightly different idea rather than a more detailed version of the same idea…” (Goel, 1995). Vertical transformation is considered as”… one where movement is from one idea to a more detailed version of the same idea…” (Goel, 1995).

In this model, preliminary design sketches are described as being fragments of ideas, where designers tend to generate a single idea and develop it through transformations (lateral or vertical) to a point when it can be evaluated, instead of generating several independent fragments and choosing between them (Goel, 1995; Goel, 2000).

Previous efforts by Goel (1995) and by Rodgers et al. (2000) to track design progress have looked at the sketch as a global entity that undergoes transformation from one design phase to the other. They did not study the breakdown of these sketches into their basic components, or trace the promotion or development of chunks of concepts throughout the different design phases.

Our approach involves going beyond lateral and vertical transformations in describing the sketching process, and exploring the underlying process flows that occur during a design phase,

just before a design phase, and just after a design phase. We argue that lateral and vertical transformations do not introduce a sufficient method to represent concept development in sketching activities throughout design phases.

3. PROTOCOL STUDY

3. 1. EXPERIMENT

We report a protocol analysis of architectural sketching to study the development of concepts in schematic and refined design phases. Protocol analysis has been used in many disciplines to study human cognitive behavior within problem-solving contexts (Kirwan & Ainsworth, 1993). In this study, we explore the sketching process and decompose it into chunks of meaningful strokes and processes. The task in the study was to design a 2-story public library. We provided the design brief (Appendix A) including information about the site, street width and location, orientation, building height, and floor square areas.

We observed two PhD students (S1 and S2) as our subjects in separate design sessions. Each session lasted approximately one hour. Both had undergraduate architectural background, and professional experience; 6 and 2 years respectively. They were asked to use color pencils in any combination and tracing paper to sketch. We used tracing paper to record stroke transfer in each design phase. They were free to use a ruler or freehand sketching. The experiment was recorded using a video camera. Each session consisted of a 5-minute introduction to the task, a 45-minute design session, followed by a 15-minute session where the subjects described their approach to the design problem and sequence of actions.

The design session was carried out in three phases. In the first phase, the subjects were asked to provide three alternatives in schematic plan drawing for the library in 20 minutes. The spaces in the design brief included a reading and sitting area, computer cubicles, bookshelves, a reception desk, and a coffee area. In the second phase, the subjects were asked to trace one of the alternatives and develop it into a refined preliminary design in 15 minutes. The subjects were asked to respond to client modifications concerning location of the building entrance and some functions, in addition to preserving one façade as a glass wall and another as a solid wall. In the third phase, the subjects were required to trace the refined design and develop it into detailed

drawings in 10 minutes. They were asked to illustrate elements of structure, materials, circulation, annotations and dimensions.

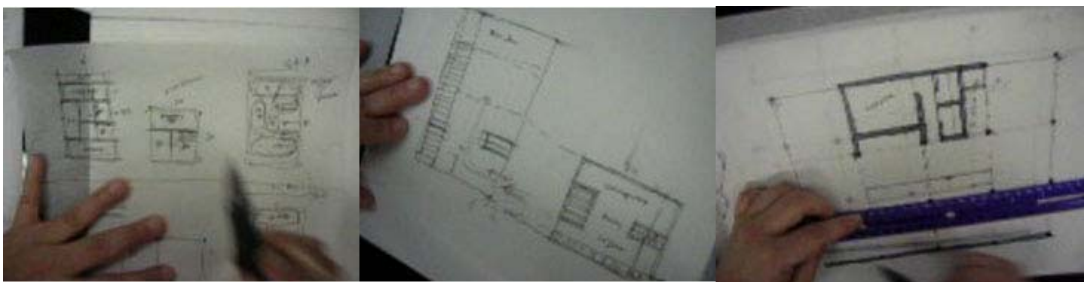
Dividing design sessions into the previous three phases played a crucial role in our study. It allowed us to track concept development through these phases, and the associated sketching behaviors within. It also allowed us to explore the sketching processes related to lateral and vertical transformation, and define process flows through the decomposition of these processes. We focus in this paper on a detailed segment of sketching behavior, explained in section 3.3.

3. 2. GENERAL OBSERVATIONS

Subject S1 spent the first 7 minutes analyzing the design brief and calculating the areas for the required spaces, and then developed three design alternatives in about 16 minutes in two stages. The first stage was a zoning diagram for the ground and first floor plans, and the sketching was in freehand drawing with a marker. The second one was a schematic plan with some detailing of furniture and partitions. This was mostly done using a thin-pointed pencil, while using the marker for outlining the outer plan walls. The three alternatives were drawn as separate entities within the same tracing paper, but with no tracing involved.

In the refined design phase, S1 developed the first alternative into a refined preliminary design. She said that the first alternative could be easily developed to match the introduced client constraints. Most of the constraints, such as building entrance, glass wall orientation and computer cubicle location, were met in the first alternative. S1 traced the plan outline, and carried out space organization within the plan with no tracing. She drew the ground and first floor plans in 7 minutes as separate entities on the same tracing paper with no tracing, and in a larger scale than in the schematic phase. S1 started drawing the section on a separate tracing paper with no tracing from the plans for a period of 3 minutes. She discontinued drawing the section, and started sketching a 3D perspective. While drawing the perspective, S1 went back and forth between the plan, section and perspective. She added details of material, cladding and shading in perspective first, and then modified the section with similar details. This was done in 12 minutes.

In the detailed drawings phase, S1 did not trace the preliminary design, but developed the drawing using a ruler in a larger scale than both previous phases. S1 started by setting the structural grid, columns, and main walls, which she hatched with the marker. She did the same for the ground and first floors. This process took about 14 minutes. S1 said that she accomplished only 40-60% of the assigned task, and that she needed more time. Snapshots of S1 sketching activities are shown (Fig. 1).



(a) (b) (c)

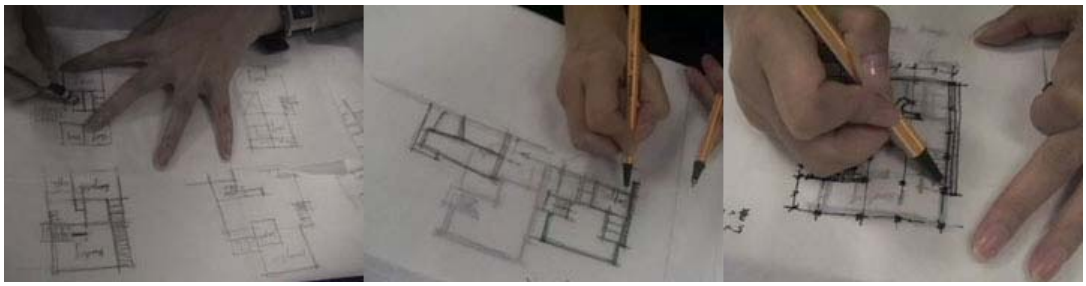
Figure 1: Snapshots of subject S1 sketching activities
(a) Schematic design phase: 2 floors for first alternative
(b) Refined design phase: 2 floors for refined design
(c) Detailed design phase: ground floor drawn with ruler

Subject S2 started by drawing the site plan for the first 2 minutes using a ruler and pencil. Instead of calculating the space areas as S1, S2 started developing schematic drawings immediately while looking at the areas in the design brief. S2 drew the ground and first floor plans for the first alternative as separate entities with no tracing. This was done in 7 minutes. S2 then developed the other two alternatives by fully tracing their precedents. She used multiple tracing papers to trace exterior and interior walls from both the ground and first floor plans. S2 accomplished the schematic phase in 20 minutes.

In the refined preliminary design phase, S2 listed down the client modifications and selected the third alternative before the end of the second minute. She said it was easy to adapt the modifications into her design. She started by responding to the building entrance modification and its consequences, emphasizing the north glass wall and west solid wall, and then worked on adapting the functions of the reading area and computer cubicles. S2 alternated between the ground floor plan, the first floor plan and the section in this stage. She also combined the use of pencils for tracing and annotating drawings, pens for hatching and emphasizing walls, and colored pens for emphasizing glass walls and materials. S2 traced the ground and first floor plans, in addition to the section. Although she did not add much detail into the section, it showed the main

form and masses of the building. She hatched some areas in those masses to indicate different materials. S2 accomplished the refined phase in 15 minutes.

In the detailed drawings phase, S2 traced the ground floor plan from the refined design phase. She started by specifying the structural grid and columns, and emphasizing elements such as the marble solid wall in the west façade using a black pen, and the glass wall using a colored pen. She began to assign the northern part of the east and west walls as glass walls. She mentioned that the form in section made her take that decision, stating that she would maintain that decision if she were to argue with the client about it. S2 also assigned basic dimensions in addition to some annotations to indicate materials for most of the exterior walls. She developed both floor plans within the allocated time. S2 said that she accomplished 80% of the assigned task for all phases, and that she needed more time in the last phase. Snapshots of S2 sketching activities are shown (Fig. 2).



(a) (b) (c)

Figure 2: Snapshots of subject S2 sketching activities

(a) Schematic design phase: tracing second alternative from the first alternative (2 floors)

(b) Refined design phase: tracing the section from refined ground and first floor plan

(c) Detailed design phase: tracing walls and structural elements from refined ground floor plan

3. 3. DETAILED STUDY RESULTS

We selected a segment of sketching activity for subject S2 to explore the underlying sketching processes (Fig. 3). Most of the sketching by S2 was through tracing, which allowed for accurate tracking of sketched strokes throughout schematic and refined design phases. More detailing and reinforcement of design elements was also observed, in addition to the accomplishment of most of the required tasks. We chose to study two design phases; the schematic and refined phase. In the schematic design phase, we focus on two of the design alternatives (drawings A and B) in

floor plan developed by S2. In the refined design phase, we study how S2 developed the alternative design according to the client constraints into a third drawing in floor plan (drawing C).

We chose these drawings to discuss the idea of lateral and vertical transformation in design. According to Goel's (1995) notion of lateral and vertical transformation, the transformation from drawing A to B is assumed to be a lateral transformation, as S2 presented a slightly different idea in drawing B, while building on some strokes in drawing A. The transformation from B to C is assumed to be a vertical transformation, where S2 worked on a detailed version of drawing B to develop drawing C. According to our assumption, a potential design concept is embedded in each stroke or group of strokes. We believe that the general labeling of the transformation processes between these drawings as lateral and vertical is not sufficient to describe how potential concepts are developed within schematic and refined design phases.

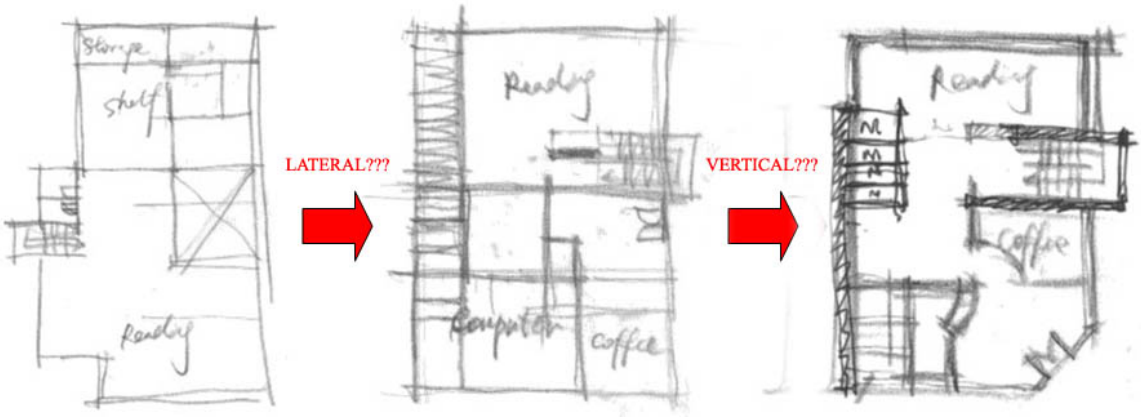


Figure 3: The three drawings in the detailed protocol study
(a) Schematic Design: alternative 1
(b) Schematic Design: alternative 2
(c) Refined Design

In the detailed study, we observe 8 minutes of sketching. Subject S2 spent 1 minute and 45 seconds sketching drawing A, 2 minutes and 25 seconds to develop a second alternative in drawing B, and 3 minutes and 50 seconds refining the alternative to develop a refined design in drawing C. All three drawings were floor plans of the designed library. S2 alternated between pencils, dark pencils, black and colored pens to emphasize certain strokes, indicate different line widths, hatching, or to accentuate some lines that were seen as significant in the design process.

Drawing A was characterized by quick strokes with more emphasis on introducing new strokes to the sketch. Drawing B was also characterized by quick strokes, with more focus on emphasizing the newly introduced strokes. In drawing C, slower strokes were observed, with more emphasis

on strokes using coloring and hatching, responding mostly to the constraints introduced in the design brief at the refined design phase.

4. ANALYSIS

4. 1. STUDYING STROKES

We view sketched strokes in design as drawing elements that contribute towards the evolution of potential design concepts. We will assume that the sequence of process flows that occur along and within schematic and refined design phases for these sketched strokes represents the gradual evolution or otherwise rejection of potential design concepts. Built on this assumption, we propose that sketching undergoes three main types of transformation along schematic and refined design phases (Fig. 4).

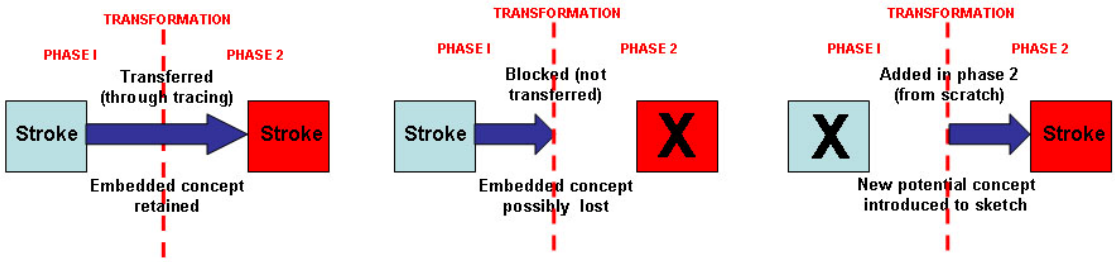


Figure 4: Three possible types of transformation along design phases

By looking at any two consecutive phases, a sketched stroke or groups of strokes can be seen as one of three cases; transferred, blocked, or added. In the first case, we assume that a transfer process occurs if a stroke or groups of strokes are traced fully or partially, i.e. carried along to the next phase. We argue that there is a probability of a potential embedded design concept being retained along this kind of process. In the second case, we assume that a blocking process occurs if a stroke or groups of strokes are not traced or carried along to the next phase. This implies that there is a probability that these strokes are not significant in this transformation stage, and consequently a probability of loss of a potential design concept. In the third case, we assume that an adding process occurs if a stroke or groups of strokes are introduced in successive design phases. This implies that there is a probability of a new potential concept being introduced to the sketch in a later phase. According to this classification, a number of possible stroke transformations exist along and within design phases (Fig. 5).

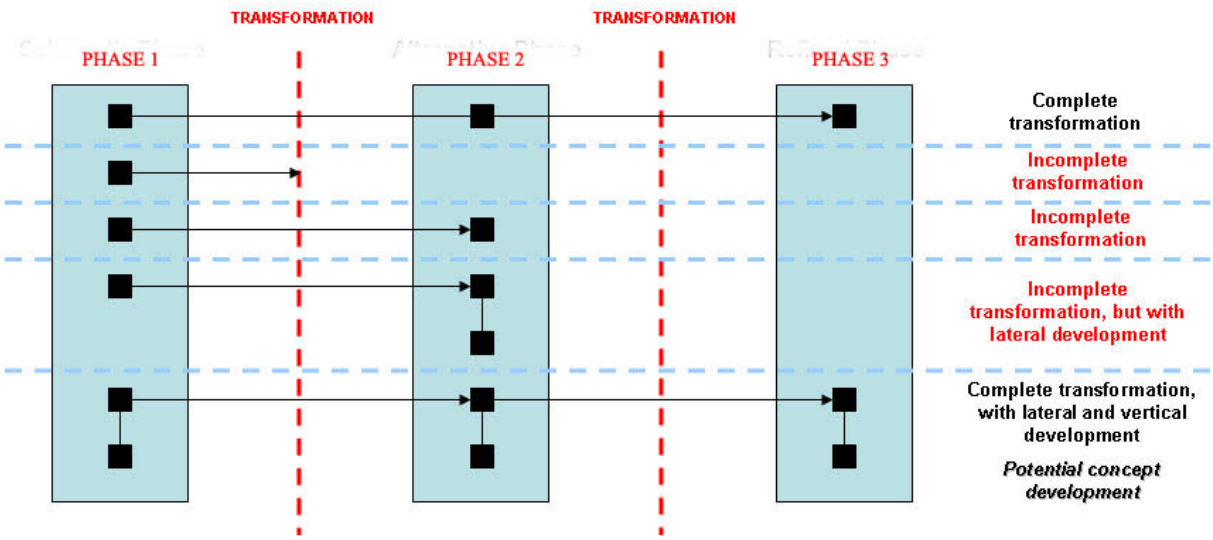


Figure 5: Transformation along and within design phases

A stroke or groups of strokes can experience an incomplete transformation by either being blocked in one of the phases, or transferred to the successor phase but blocked at the next phase. A stroke or groups of strokes can also be laterally developed within one phase, i.e. if a stroke or groups of strokes draws the attention of the designer to "*see* a part of the stroke *as*" a potential of another individual stroke or group of strokes, and consequently another potential concept within. If a stroke is both transferred along a design phase and laterally developed within the phase it belongs to, but is blocked at the last phase, it is also considered an incomplete transformation. A complete transformation in this case can only occur if full transfer occurs along all design phases, or if a stroke is both fully transferred and laterally developed. In the second case, we assume that there is a stronger probability of development of a potential concept. We have described the transfer of strokes along design phases and a detailed instance of lateral development, different than lateral transformation (Goel, 1995). We have not distinguished our understanding of vertical transformation (Goel, 1995). We show in the next section the coding scheme we used in the protocol study to describe accurately the process flows that occur in sketching.

4. 2. CODING SCHEME

The sketched strokes in each drawing were labeled according to the time sequence in which they

were drawn (Fig. 6). We recorded the starting and ending time for each individual stroke. We mean by a sketched stroke any type of line drawing drawn on the tracing paper with any pen, excluding text and annotations. We recorded instances of strokes traced from one drawing to the other, including labels of the precedent and successor stroke, to track how strokes evolved from previous drawings. We also recorded whether a new stroke was introduced to or deleted from the sketch in any design phase or drawing.

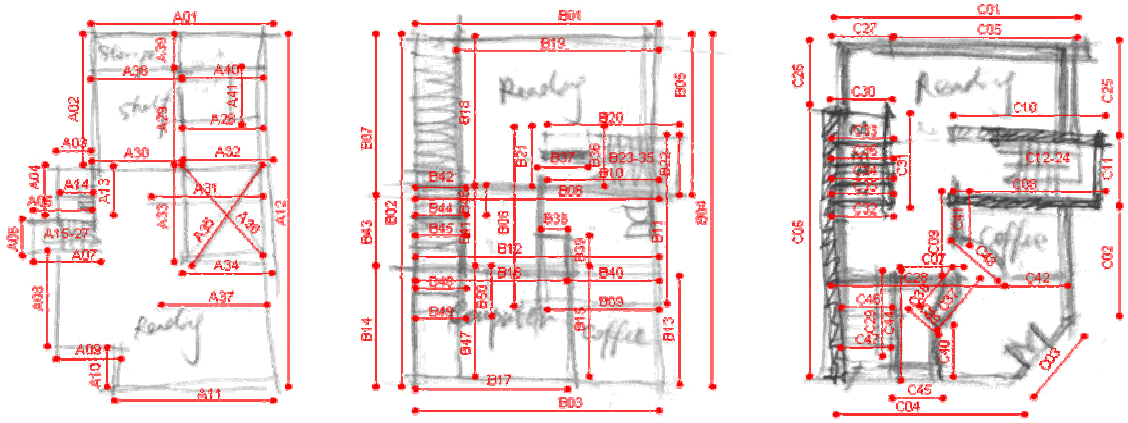


Figure 6: Labeling sketched strokes according to their drawing sequence in drawings A, B and C

We recorded the actions of repetitions of strokes, using different colors, hatching, drawing double lines to indicate for example a wall, adding elements such as doors, windows, columns,…etc. We laid out this information in tables for each drawing (Appendix B), illustrating the following:

Stroke Label: This indicates the drawing (A, B, or C) and serial number in time sequence when the stroke was recorded, e.g. A30.

Start time and end time: This indicates the duration of the stroke.

Process: This is a description of the sketching activity, e.g. trace from previous, repeat line, modify to double line,…etc.

Process type: This includes all the main coded activities that occurred during sketching:

ADD: This includes introducing any new stroke or group of strokes to a specific drawing, which did not originally exist in the precedent drawing.

CP (Cross propagation): This process denotes tracing a stroke from a previous drawing, denoting a potential embedded concept being transferred further elaboration.

DEL (Delete): This can denote the activity of deleting a stroke by the designer, or the process of a propagation block, where a stroke from the precedent drawing is not carried on to the current one.

We classify the previous three processes under "**propagation process**" along design phases.

LP (Lateral Promotion): This process denotes lateral development, where a stroke is modified laterally within the same phase, e.g. repeating the stroke but with a change in length to indicate shift of focus to a new element or space in the design, which gets emphasized as a separate entity in successive phases.

REP (Repeat): This denotes fully repeating a stroke within one drawing. A full repetition indicates a notion of emphasizing the stroke, which consequently would lead to retaining a potential embedded concept.

CLR (Color): This denotes using a different color or pen type to emphasize a stroke. It indicates emphasis of a stroke for further development by showing materials or texture of the represented design element.

HAT (Hatch): We assume that this process indicates a strong probability of retaining a stroke for further elaboration, possibly for indicating materials or providing annotations in successive phases.

WID (Line width): This denotes using multiple strokes to change the width of an existing stroke, whether it is repeated or traced, e.g. modifying a stroke to a double line to indicate a wall. We assume that the activity of changing line width for a stroke in a specific drawing would indicate a strong probability of developing that stroke in further drawings.

SUP (Supplementary Element): This process denotes supplementing a stroke with further information, e.g. adding a door, window or structural element. We assume that carrying out that activity would reflect a strong probability of developing that stroke in further drawings.

We classify the previous five processes (REP, CLR, HAT, WID, SUP) under the category **VP (vertical promotion)**. We introduce the "**promotion process**" to indicate a strong probability of design concept promotion within each phase for each individual stroke or group of strokes. We define **lateral promotion** as a process where a strong probability of the emergence of lateral strokes and consequently potential lateral concepts exists for a given stroke. Vertical promotion is the process where a strong probability of the elaboration of a stroke and consequently a potential embedded concept exists for a given stroke in a given design phase or drawing.

Precedent Stroke Label: This shows the serial number of the stroke that preceded the current stroke, e.g. “stroke label: C24, process: trace from previous, precedent stroke label: B35” means that stroke C24 was introduced to drawing C as a result of being fully traced from stroke B35 in drawing B. A “NO PRECEDENT” statement indicates a new stroke added to the sketch. A segment of the process analysis tables for the different process types is illustrated (Fig. 7).

SKETCHING PROCESSES INVOLVED IN GENERATING GROUND FLOOR PLAN IN REFINED DESIGN PHASE (DRAWING C)													
STROKE LABEL	START	END	PROCESS	PROCESS TYPE									PRECEDENT STROKE LABEL
				PROPAGATION			PROMOTION						
				ADD	CP	DEL	LP	VP					
								REP	CLR	HAT	WID	SUP	
C24	22:48	22:48	Trace from previous		■			■					B35
C24	22:50	22:50	Repeat line					■					C24
C25	22:52	22:53	Trace part of line, change length		■		■						B05
C25	22:53	22:53	Modify to double line								■		C25
C10	22:54	22:56	Modify to double line										C10
C25	22:58	22:59	Repeat line					■					C25
C05	23:00	23:00	Repeat line										C05
C26	23:04	23:05	Trace part of line, change length		■		■						B07
C06	23:05	23:09	Modify to double line								■		C06
C27	23:10	23:10	Repeat part of line, change length				■						C01
C26	23:11	23:11	Repeat line					■					C26
C28	23:14	23:15	Repeat part of line, change length				■						C07
C29	23:16	23:17	Trace from previous		■								B47
C28	23:18	23:19	Modify length of line				■						C28
C28	23:20	23:21	Repeat line					■					C28
C06	23.21	23.23	Repeat with diff color & line type						■				C06
C06	23.24	23.27	Hatch with diff color & line type						■	■			C06
C01	23.30	23.32	Repeat with diff color & line type						■				C01
C26	23.33	23.33	Repeat with diff color & line type						■				C26
C26	23.34	23.35	Modify to double line w/diff color&lt						■		■		C26
C30	23.39	23.40	Introduce new line	■									NO PRECEDENT
C31	23.40	23.41	Introduce new line										NO PRECEDENT
C32	23.41	23.41	Introduce new line										NO PRECEDENT

ADD Introduce new stroke to sketch

CP Cross Propagation of strokes between drawings

DEL Deletion of stroke within drawing, or propagation block to next drawing

LP Lateral Promotion of strokes to divert to lateral concept

VP Vertical Promotion of stroke for further refinement and elaboration

REP: Repeat CLR: Color HAT: Hatch WID: Line width SUP: Supp. element

Figure 7: A segment of the process analysis table showing process types for sketched stroke

4. 3. PROCESS FLOWS

Some statistics for the processes in drawings A, B and C for subject S2 are illustrated (Fig. 8).

	Drawing A	Drawing B	Drawing C
Total Strokes	57	99	111
Duration	87 sec	145 sec	230 sec
Stroke/time ratio	Stroke every 1.53 sec	Stroke every 1.53 sec	Stroke every 2.28 sec
Added Strokes (ADD)	41	27	11
Cross Propagated Strokes (CP)		8	26
Deleted Strokes (DEL)		34	24
Laterally Promoted Strokes (LP)		20	14
Repeated Strokes (REP)	14	41	29
Colored Strokes (CLR)			16
Hatched Strokes (HAT)		2	4
Strokes w/supplemented features (SUP)	2	1	1
Strokes w/modified line width (WID)			10

Figure 8: Statistics from process analysis tables for drawings A, B and C for subject S2

From the statistics of stroke process types in fig. 9 and the process analysis tables for drawings A, B and C, we observed that the number of ADD strokes decreased along the succession of drawings from 41 strokes in drawing A to 11 strokes in drawing C. In drawing A, most of the strokes were newly introduced. In drawing B, most of the strokes were introduced to re-allocate the building spaces, stair location and building entrance. Most of the ADD strokes in drawing C were introduced to change the location of the building entrance towards the southeast, re-allocate the computer cubicles and coffee area, and introduce other additional shelves and storage areas.

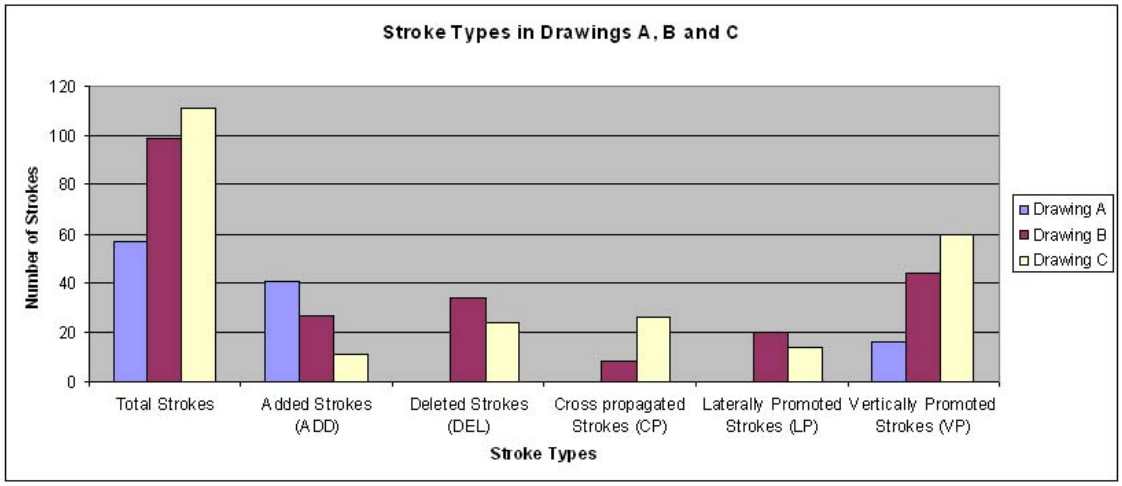


Figure 9: Stroke process types in drawings A, B and C for subject S2

The number of CP strokes increased from 8 strokes in drawing B to 26 strokes in drawing C. In drawing B, the strokes that were cross propagated from drawing A were traces of outlines of the building and a few interior walls. In drawing C, most of the CP strokes emphasized the outlines of the building, the staircase and most of the interior space walls.

The number of DEL strokes decreased from 34 strokes in drawing B to 24 strokes in drawing C. The number of LP strokes decreased from 20 strokes in drawing B to 14 strokes in drawing C. Most of the LP strokes in drawing B were introduced as re-allocations for new interior space walls. In drawing C, the LP strokes mainly introduced slight adjustments to existing walls for defining spaces and interior circulation.

The number of VP strokes increased along the succession of drawings from 16 strokes in drawing A to 60 strokes in drawing C. In drawing A, the VP strokes were basically repetitive strokes for the exterior walls of the building. In drawing B, there were more repetitive strokes for exterior and interior walls and some emphasis on the west wall through hatching. In drawing C, we observed

less repetitive strokes, but more coloring and hatching, especially for the north glass façade and west solid wall.

From the previous observations, we assume that the more developed the design phase, the fewer the ADD and DEL strokes. We assume that fewer strokes were added as a result of the "seeing" process that occurs in sketching while tracing from precedent drawings. Novel strokes were introduced in the schematic drawings and more CP strokes during the refined phase. In drawing C, most of the ADD strokes were introduced as a response to the new client constraints, and the least were novel strokes. Similarly, fewer strokes were deleted in the refined phase, as more strokes were cross propagated for further elaboration.

LP strokes slightly decreased from drawing B to C. We view LP strokes as phase independent. At any phase, the designer can "*see* strokes *as*" a potential for other lateral strokes and develop lateral concepts. We assume that this accounts for the insignificant decrease in LP strokes. We assume that more VP strokes were introduced in the refined phase than the schematic phase to emphasize important elements, such as the glass façade and west solid wall. S2 used multiple repetitions, coloring and hatching to emphasize location, orientation and materials for those walls.

4. 4. STROKE PROPAGATION ACROSS DRAWINGS

From the process analysis tables, the different sketching processes were grouped to compose the flow diagrams shown in Appendix C. The diagrams define all the relationships for each individual stroke in the sketches for the three drawings. They provide time-stamped information about stroke-to-stroke process flows for all types of propagation and promotion processes. Fig. 10 shows the location of one of the sketched strokes and its corresponding precedents and successors along drawings A, B, and C.

Figure 10: The evolution of a stroke throughout phases A, B and C

Propagation process flows are shown in fig. 11. A stroke is added (ADD) to the sketch in drawing A as A30 in minute 12.51. Stroke A30 was cross propagated (CP) at minute 14.59 to produce stroke B06. At minute 22.30, stroke B06 was then cross propagated (CP) again to produce stroke C08. This indicates a process of full propagation through all drawings. Stroke B42 in the same diagram is blocked (DEL) in drawing B, as it is not transferred to drawing C. Although there seems to be a stroke similar in location in drawing C to stroke B42, the video recordings show that subject S2 had removed the tracing paper before that moment, worked on drawing C with no tracing paper underneath, and introduced the stroke as a new one. It cannot be inferred that stroke B42 was a source of cross propagation for that stroke in drawing C.

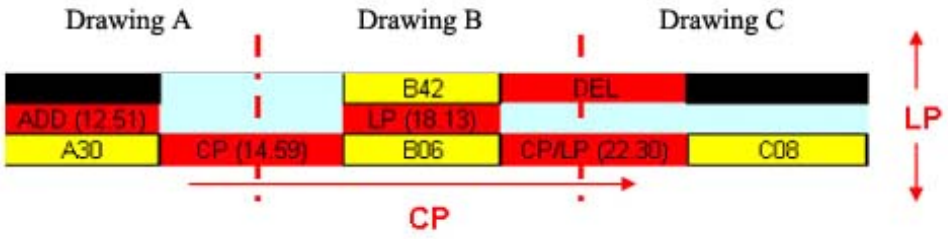


Figure 11: Propagation and Lateral Promotion process flow diagram starting with stroke A30

4. 5. STROKE PROMOTION WITHIN DRAWINGS

As shown in fig. 11, two lateral promotions are observed. One of them is associated with a cross propagation activity, indicating a process of tracing stroke B06 at minute 22:30, but by introducing a certain modification of stroke length, allowing for a lateral promotion to occur at the same time, to produce stroke C08, which is considered a variation on stroke B06. The other lateral promotion occurs within drawing B, indicating the introduction of stroke B42, as a stroke length variation on stroke B06.

Time stamped vertical promotions for all strokes linked within a CP process are illustrated (Fig. 12). No VP processes exist for stroke A30, since it was introduced and immediately cross propagated. As for stroke B06, we recorded five identical vertical promotions, which denote extensive emphasis on that interior wall. As for stroke B42, we recorded two REP activities and one HAT activity. Looking at the propagation process reveals that stroke B42 was deleted (DEL) from the sketch, thus reducing its probability of further promotion.

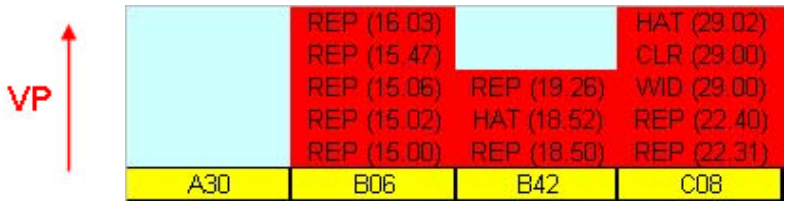


Figure 12: Vertical Promotion process flow diagram for strokes A30, B06, B42 and C08

As for stroke C08, we recorded two REP activities, one CLR activity, one WID activity, and one HAT activity, indicating four out of possible five VP activities. We assume that this number of vertical promotions indicates a high level of emphasis, providing a higher probability for concept development in further phases. We assume that these results for stroke C08 show that the location and dimensions of the corresponding wall are settled and ready for detailed refinement.

Concerning complete and incomplete transformations, the flow from A30 through B06 and to C08 is considered a complete transformation. The combination of all three processes (CP, LP, and VP) generates a complete transformation provided that all end points of either process continue to be promoted. Although B06 exceeds C08 by one LP activity, the end product of that LP stroke is a DEL activity. On the other hand, both C08 and B06 have the same number of vertical transformations, but C08 excels in variety of activities. We assume a higher probability of potential concept promotion at this stage for stroke C08.

5. DISCUSSION AND FUTURE WORK

We argue that the types of transformation occurring in the design process are not limited to the global terms, lateral and vertical transformation. It is not the whole phase that is transformed, but each stroke or group of strokes have their own identity and associated potential concept. This potential concept is propagated along the stroke through design phases, and gets promoted or blocked according to the type of process flows.

We aim at expanding the notion of lateral and vertical transformation. For example, the fewer strokes are propagated from one design phase to another (more DEL activities and less CP activities), the more novel the strokes that are introduced to the sketch (more ADD activities) and consequently a nearer notion to conventional lateral transformation. The more strokes are propagated (less DEL activities and more CP activities), the more potential ideas are carried into depth in successive phases (less ADD activities), emphasizing the notion of vertical

transformation. We can view both propagation and promotion activities as components of both notions of lateral and vertical transformation, since variations among these components contribute to the lateral or vertical development of a concept.

We do not see a clear distinction between laterally and vertically developing a design. We use characteristics of propagation, lateral and vertical promotion instead to describe every concept entity. We view it as a dynamic process that can change both within the phase and along two consecutive phases. We assume that this decomposition of process flows makes it easier to track design development in time across their precedents and successors. Instances of vertical or lateral promotion could be identified along the timeline, and their networked structure could be queried to track design development.

Providing computational support is significant for further research. By embedding knowledge of process flows in databases containing information about design strokes and networks of associated processes, propagation and promotion processes can be modeled computationally. This can have potential applications in architectural design and education. Educational institutions could implement such a model to show students hidden lines of thought for famous architectural projects. Another parallel line of implementation is the tutor-student model, where students usually struggle to understand tutors' instructions. In architectural firms, novice designers could use such a tool to understand underlying concepts behind sketches of senior professional designers.

CONCLUSIONS

We decomposed sketching processes into process flows to track design development in concept design phases. We conducted a protocol study to extract the detailed activities involved in freehand sketching, known as the medium most suitable for architects to externalize their ideas. We defined a set of process types; cross propagation, lateral promotion and vertical promotion, which describe the behavior of individual strokes throughout design phases. Through the detailed process flows between sketched strokes, we expanded the conventional notion of lateral and vertical transformation in design. We argue that the defined process flows can be used as design aids in architectural practice and education for tracking concept design development.

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APPENDIX A: PROJECT DESIGN BRIEF

A STUDY ON DECOMPOSING SKETCHING PROCESSES

Thank you for participating in this study, Please take a couple of minutes to fill in your personal information, and then read the instructions below.

Name:

Academic Background:

Years of Professional Experience:

PROJECT DESCRIPTION

The task in this study is to design a 2-story public library in a site with foot print dimensions 30m X 40m. The longer side is in the north-south direction. The site is surrounded from the east and south directions by two 20m wide streets, from the north direction by a park, and from the west direction by a neighboring building. The area of the first floor is half the area of the ground floor, which is raised 60cm above the street level. The overall interior height of the building is 8.0m.

INSTRUCTIONS

This study is carried out in 3 phases with a total duration of 45 minutes, followed by a brief questionnaire for 5 minutes. Please use the provided tracing paper. You can use a ruler or measuring scale if required, and sketching pencils with any combination of colors.

PHASE 1 (20min. session)

You are required to develop THREE ALTERNATIVES in schematic plan drawing for the given public library, provided the following functions:

- Reading and sitting area (500m2)
- Computer cubicles area (300m2)
- Book shelves (400m2)
- Reception desk area (40m2)

- Coffee and snacks area + preparation (80m2)
- Storage rooms area (120m2)
- Restrooms (4 male units, 5 female units)
- Suitable circulation area

PHASE 2 (15min. session)

Now TRACE one of the alternatives and develop it into a preliminary design, consisting of one plan and one section. The client has made the following modifications. Please respond accordingly:

- Entrance has to be from southeast direction
- All the north façade is to be a glass wall, and the west façade is a totally solid wall
- Computer cubicles have to be on upper floor
- Height below upper floor is set to 5.0m

PHASE 3 (10min. session)

Now TRACE the preliminary design and provide detailed drawings (pre working drawings) for the refined plan and section, briefly specifying the following information:

- Structural system
- Stairs and ramps
- Dimensions and levels
- Materials for walls and floors

Thank you for participating in this study. Please take 15 minutes to fill in the following brief questionnaire which will be of significance to the success of this study.

1- What differences did you realize in your drawing and sketching method in the three phases?

2- Can you briefly specify how you approached the design problem?

3- When exactly did you need to specify accurate measurements and use a ruler versus freehand sketching?

4- Did you need to assign different colors for certain design elements? At which phase was that, and what are those elements?

5- Did you feel at any time during the study that you needed an additional tool besides sketching? If yes, please specify its type, whether physical or computational.

6- Do you think the duration of the experiment was enough for all phases?

7- Do you think you have accomplished the whole task given? If not, what percentage have you been able to accomplish in each phase?

8- In your opinion, how could this study be improved as setting, duration, program,…etc.?

Thank you for your patience and participation

APPENDIX B: PROCESS ANALYSIS TABLES

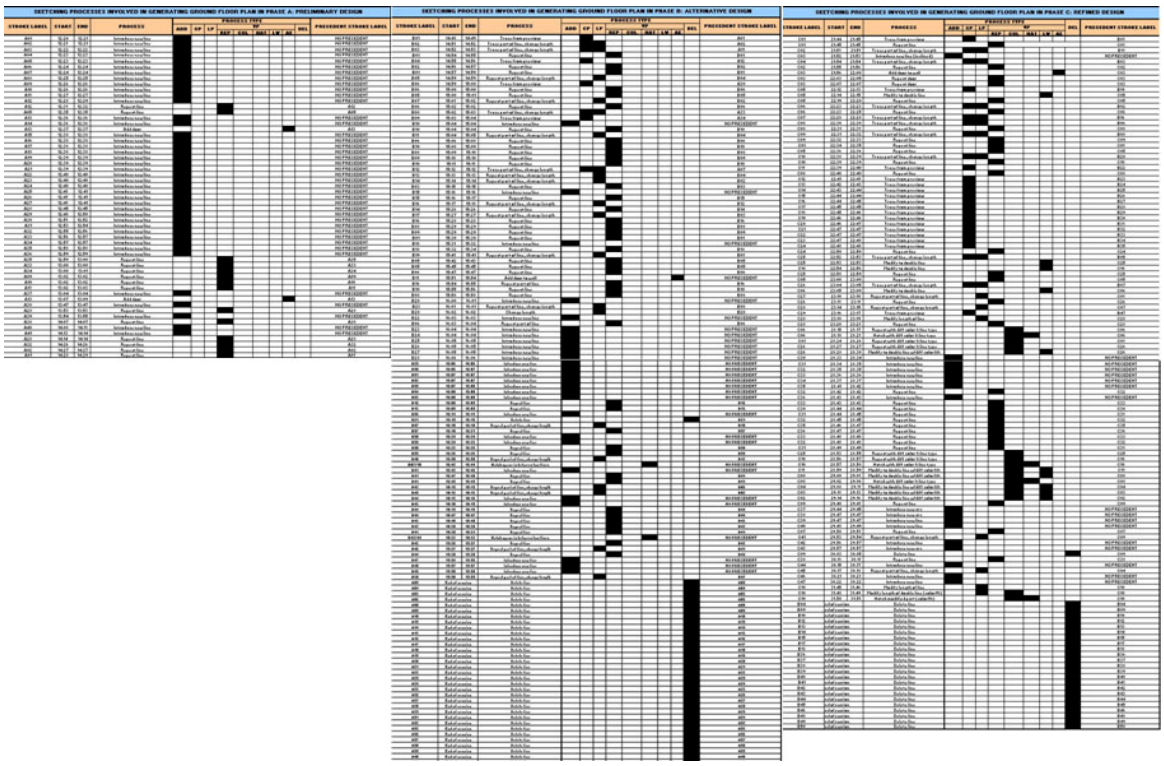

Figure 13: Tables showing the analysis of process types for drawings A, B and C

APPENDIX C: FLOW OF SKETCHING PROCESSES

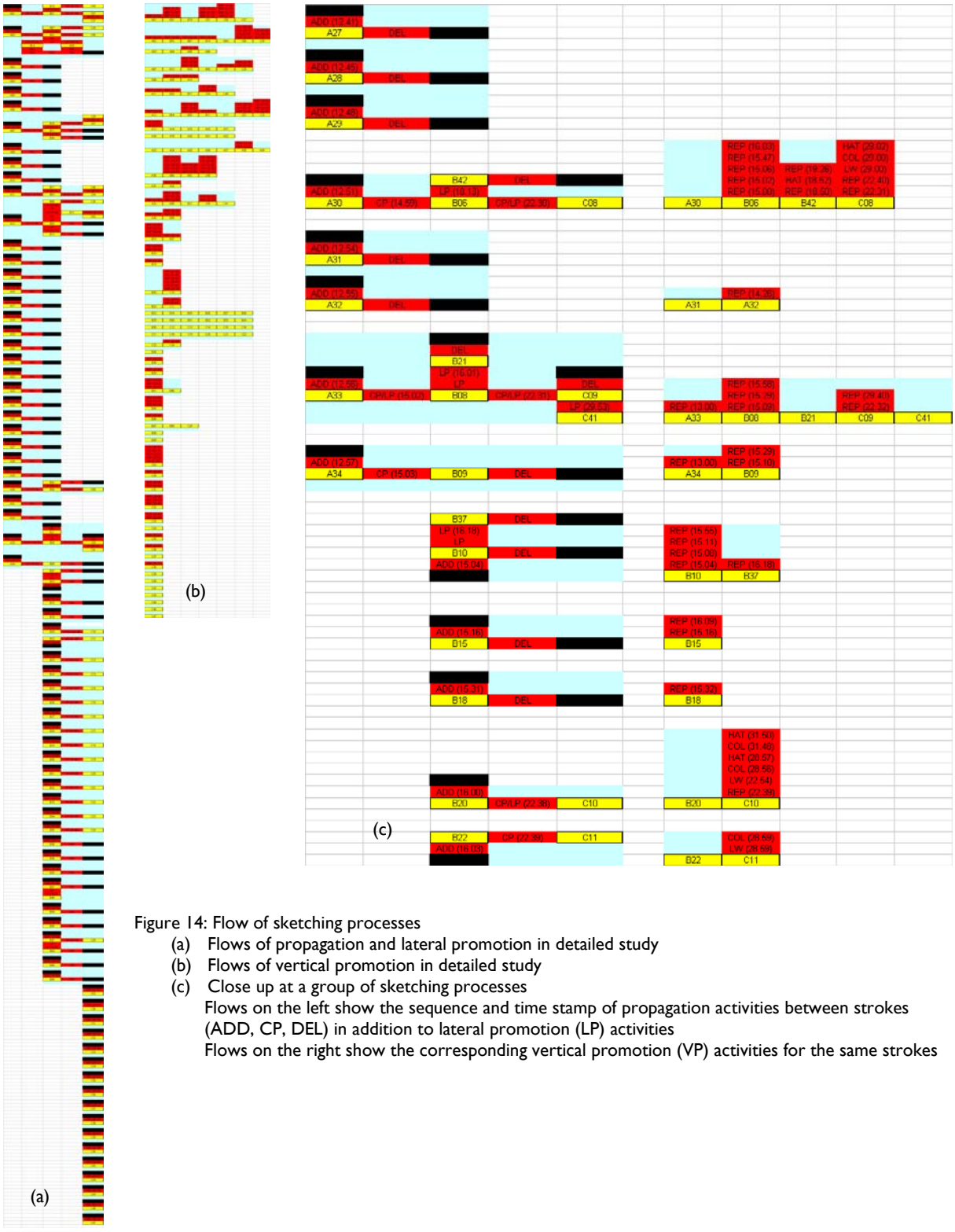

Figure 14: Flow of sketching processes

(a) Flows of propagation and lateral promotion in detailed study
(b) Flows of vertical promotion in detailed study
(c) Close up at a group of sketching processes

Flows on the left show the sequence and time stamp of propagation activities between strokes (ADD, CP, DEL) in addition to lateral promotion (LP) activities

Flows on the right show the corresponding vertical promotion (VP) activities for the same strokes