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# Analysing how constraints impact architectural decision-making

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*Architectural design projects are characterised by a high number of constraints. Along with planning, energy performance and fire safety regulations, current designers have to face constraining factors related to budget, acoustics, orientation, wind turbulence, accessibility for the disabled, and so forth. These constraints steer the design process implicitly and explicitly in certain directions as soon as architectural designers aim at satisfying design briefs. We aim in this article at analysing the impact of such constraints on the design process. At this end, we have studied four design sessions in a particular (student) design use case. In analysing these four sessions, we used linkography as a method, because this appeared to be one of the better options to obtain a more quantitative assessment of the design process. The linkography method was combined with an interview of the student design team, in order to check the correctness of our conclusions.*

*Keywords: constraints, design process, design thinking, linkography, requirements*

## 1 Introduction

Are constraints in architectural design considered to be limitative (constraining), or are they key reference points in a variety of parametric possibilities? Are constraints omnipresent during the design process or are they considered only until they have been 'resolved'? Does the set of requirements change during the design process? Which parameters are chosen by designers to reply to a specific design situation with a number of given constraints? Where does parametric freedom and parametric creativity come from? To make an analysis of a number of these research questions about the role of constraints and parameters in the design process, we have studied a particular design use case, in which a design team of two architectural design students designed in reply to a specific design brief containing a particularly high number of constraints. For this particular use case, four sessions were analysed in which the design team presented the latest developments in their design to the supervising design teacher. A discussion followed during each of these design sessions in which the design was not only re-evaluated, but in which the design was also redirected in response to certain constraints that were not met. We used linkography as a method for analysing these four sessions, because it allows to obtain a more quantitative assessment of the design process [6]. The linkography method was combined with an interview of the student design team, in order to check the correctness of our conclusions.

### 1.1 Designers as practitioners

With the emerging interpretation in the 1970's of the design process as a process in which 'wicked problems' [32] or 'ill-structured problems' [35] are to be re-solved, over and over again, design was more and more considered as a practice or a discipline in its own right. Newly emerging theories typically acknowledge the complexity of the design process and the role of design thinking within this process. Critical in this understanding is the role of parameters and constraints in this ‘design as a practice’. A design situation is not considered as a design ‘problem’ that is defined by a well-structured set of constraints, and in which a number of adjustable parameters is available. Instead, a design situation is now understood as a snapshot, in terms of time, in the overall design process, in which a limited number of constraints and parameters are taken into account by a designer, in order to ‘satisfice’ the design situation, as interpreted at that moment, into an alternative design situation [35].

A key role is taken here by the designer as a decision-maker. Designers are considered to be reflective practitioners [33], and, as such, they continuously decide which constraints they wish or do not wish to adhere to, and which parameters they wish to use in what way. In contrast to the earlier belief of designers having a ‘problem-focused’ strategy, they are now thus believed to having a more ‘solution-focused’ or ‘goal-oriented’ strategy instead [25]. They proceed forward through the design process, continuously facing new design situations and addressing them as they see fit in order to obtain the goal they have in mind at that specific moment in time. After addressing these design situations, this goal is typically adjusted based on the reflective ‘back-talk’ of the design situation [33], thus resulting in a co-evolution of problem space and solution space (see also [27,31]).

Additional to this context of decision-making by designers as practitioners, Donald Schön [33] also indicated that design thinking depends on the ‘repertoire’ or knowledge and experience of the designer. So, the context and background of designers play key roles as well on the decision-making processes of those designers. This context and background is often said to influence the design through a kind of analogical reasoning or case-based reasoning (see for instance [7,9,14,28]). Analogical reasoning is typically explained as the cognitive ability to think about relational patterns [13,16,22,37]. It allows one to find a structural alignment or mapping between a base and a target pattern residing in (partially) different domains [2,13,15,24,37]. During ‘design practice’, architectural designers thus continuously make alignments between the current design situation and previously experienced design situations (= analogy). Relying on such alignments, designers infer which action to take for specific design situations and hence move forward.

### 1.2 Analysing design practice using linkography

In this paper, we document part of our analysis of the impact of constraints on decision-making by designers. We used the following method in making this analysis. Design processes, as interpreted above, are often analysed using verbal protocol analysis [4,5]. The strategy is to get people to verbalise their thoughts while performing a task. These thoughts are then transcribed and analysed in order to find the cognitive processes behind the actions [26]. Example protocol analysis studies are documented by Ennis & Gyeszly [1] and Kavakli & Gero [21]. In the domain of (architectural) design, many protocol analyses are performed using ‘linkography’. Linkography is a method for representation and analysis of design processes focusing on links among design ideas. The method was first introduced to protocol analysis for assessing the design productivity of designers [6]. It was then further developed by Goldschmidt [10,11,12] and used by others [17,18,20,23,36]. Linkography has been established as a quantitative evaluation technique in protocol analysis to study designers’ cognitive activities.

In order to produce a linkograph, the recorded design protocol is transcribed and subdivided into small segments of approximately one sentence. This typically results in a spreadsheet file with a chronological list of all statements made in the design process. Each resulting segment is considered to be a design move and given a sequence number, typically using the same spreadsheet file. Goldschmidt defines a 'design move' as *"a step, an act, an operation which transforms the design situation relative to the state in which it was prior to that move"* [10]. Second, the protocol study is analysed for associations between the distinct design moves, resulting in a network of links between the design moves [19], which can also be recorded in the same spreadsheet file. Goldschmidt hereby distinguishes two types of links: backlinks (links from a particular design move to a preceding design move) and forelinks (links from a particular design move to a subsequent design move). The way in which these two types of links come about, and the way in which they ought to be interpreted is comprehensively outlined by Goldschmidt in 1995 [10], so we will not elaborate on these interpretation guidelines here.

Using a linkograph, typically recorded in the earlier mentioned spreadsheet file, the design process can be analysed in terms of the patterns in the linkograph. Using the Link Index (LI) and Critical Moves (CM) parameters, a quantitative analysis can be made of the protocol study [8,10]. The LI parameter equals the ratio between the total number of links and the total number of design moves in the linkograph. A high link index then supposedly indicates a productive design process, as the produced design moves are highly related to each other, and many of the links thus were productive in creating a coherent design process. The CM parameter indicates design moves with a high number of forelinks or backlinks. A critical move can thus be understood as a design move that had a high impact on the design process, and, as such, also on the eventual design product. Note that Kan and Gero [19] argue that the LI and CM parameters are not the best indicators of design productivity, by arguing that a fully saturated linkograph, which thus has a high LI and a high CM number, indicates no diversification in ideas, hence less design productivity. They point towards using entropy measures as indicators of design productivity. Low entropy measures hereby indicate high predictability, less innovation and thus a low design productivity in the design process [18]. We will rely on both measures (LI and CM; entropy) in the current paper.

To further improve the analysis of a linkograph, a Function – Behaviour – Structure (FBS) ontology [3] can be used. The terms used in the ontology are schematically shown in Figure 1, for reference.

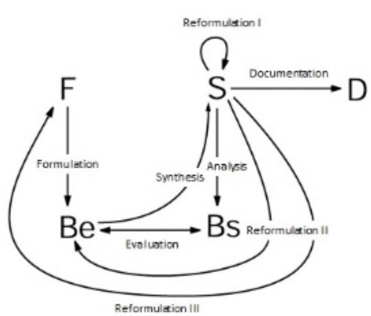


*Figure 1 Schematic overview of the FBS coding scheme*

The FBS ontology allows coding the character of the design moves identified in the linkograph. The coding scheme consists of the six following codes.

- Requirements (R)
- Function (F)
- Expected Behaviour (Be)
- Behaviour derived from structure (Bs)
- Structure (S)
- Documents or design descriptions (D)

A brief description of the FBS ontology and its six codes is given by Kan et al. [20], so we do not elaborate on this any further in the remainder of this paper. When combining the FBS ontology and linkography, the kind of change initiated by every single design move in a linkograph can be formally characterised. The design process is hereby considered as a process that starts from a set of requirement (R) and function (F) statements, which are continuously analysed (Bs), evaluated (Be) and synthesised into structure (S) statements. Eventually, documentation (D) statements are produced, documenting the structure coming out of final design decisions. After encoding, eight design transformation types can be considered (Figure 1) [19-20]: formulation (F -> Be), synthesis (Be -> S), analysis (S -> Bs), evaluation (Bs <-> Be), documentation (S -> D), reformulation I (S -> S), reformulation II (S -> Be), and reformulation III (S -> F). These transformation types will be referred to below as ‘FBS processes’.

## 2 Case study

### 2.1 The design brief: refurbishing high-rise buildings

In order to formulate preliminary answers to the questions posed at the start of this paper, the design thinking behaviour was analysed for a team of two students in the design studio Architecture & Construction at Ghent University. The assignment of this studio was to design the refurbishment of three outdated high-rise apartment buildings (Figure 2). The three towers are located along the A12 motorway in Antwerp. Furthermore, the students were asked to investigate to what extent the concept of co-housing can be accommodated in this high-rise type of building. The design brief is highly constrained by its location. The location between a residential area and the busy motorway presents a delicate urban context. Other constraints need to be addressed as well:

- The buildings on the site need to incorporate about three hundred living units along with the facilities needed for *co-housing* and a *parking area* large enough to accommodate needs of the inhabitants and their visitors.
- Attention should be paid also to the *quality of the area surrounding* the high-rise buildings. The combination of the residential area, the area surrounding the high-rise buildings and the high-rise buildings themselves present considerable challenges in terms of *scale* and *feeling of safety and comfort*.
- *Sunlight* needs to penetrate not only into the building units within the high-rise buildings, it also needs to reach the residential area and the area surrounding the high-rise buildings.
- Considerable *fire safety* and *accessibility* constraints are present as well in the kind of high-rise buildings in the design context. For instance, fire safety and accessibility regulations implicate the need for

compartmentalisation measures, the need for large, separate evacuation staircases, the introduction of circulation shafts enclosed with fire doors, the prohibition of apartments spanning three floors, and so forth.

- The need for *privacy* within the living units.
- *Fluctuating wind turbulence* on the terraces and at the base of the high-rise buildings.
- *Structural constraints* inherent to any high-rise building.

*Figure 2 Aerial view of the high-rise apartment building site that is to be refurbished (image from Google Maps)*

This task was to be completed within three months (October – December 2013). Every week, the design teams had to give a slideshow presentation, with drawings showing the recent status and advancements of their design. During these presentations, the design teacher(s) had the opportunity to give feedback, resulting in an intense and pro-active conversation between teacher and student design team. As indicated above, a particularly high number of constraints was included in the design brief of this studio, including constraints regarding fire safety, building use (co-housing living units), comfort, sunlight penetration, accessibility, privacy, wind turbulence, structure, and so forth.

*Figure 3 Design relying on an implantation of eight towers (begin November 2013)*

*Figure 4 Bird perspective of the seven towers in the final design proposal (end December 2013)*

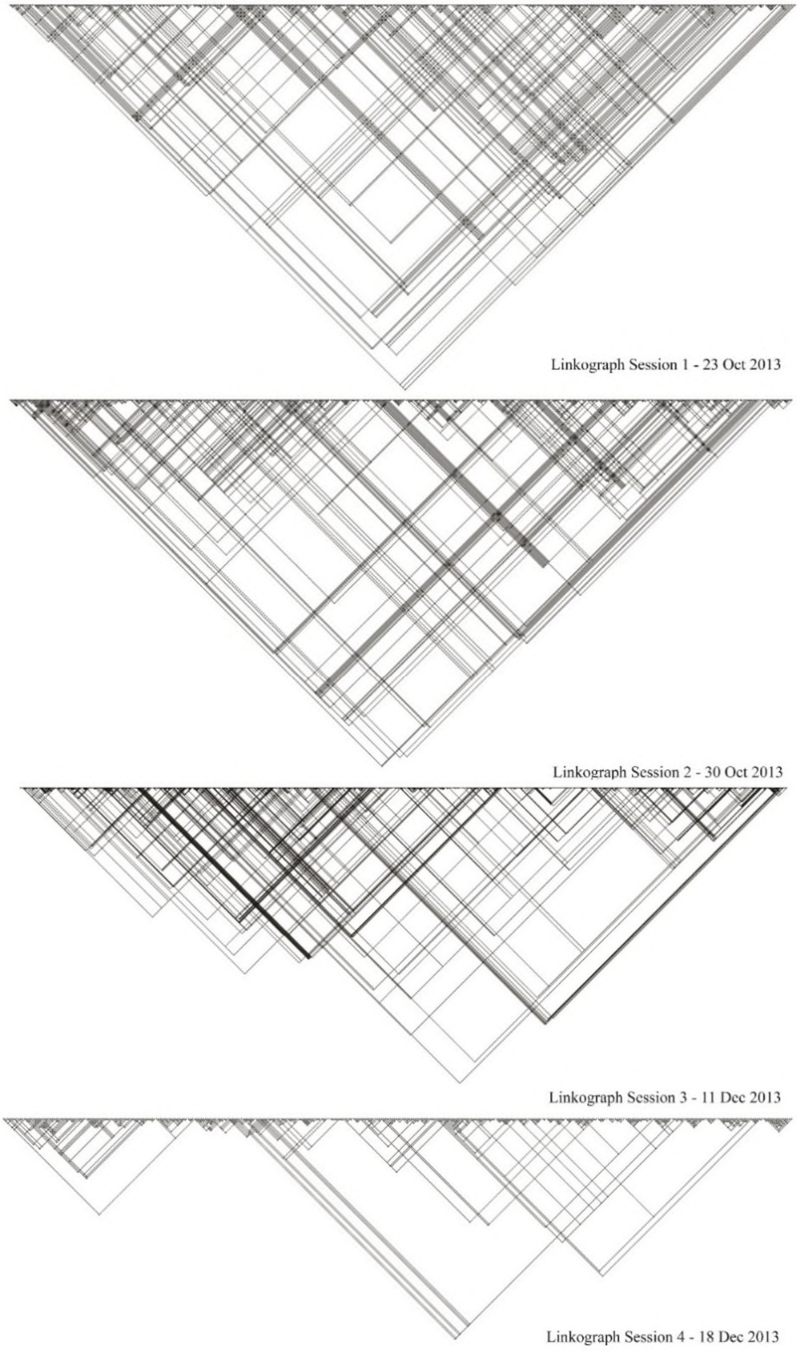


*Figure 5 The four generated linkographs, shown in a chronological order from top to bottom. For each design session, all design moves are chronologically arranged along a line from left to right. Diagonal lines and dots then indicate how the diverse design moves are linked, resulting in the four graphical displays given here. A full resolution image of the linkographs can be found at [30].*

Throughout the three-month design process, diverse configuration and design options were considered. Figure 3, for instance, shows a configuration of eight high-rise buildings, organised in two groups of three buildings and one group of two buildings. By doing so, the co-housing constraint is implemented not only on a collection of living units (living unit scale), but also on a collection of tower units (tower scale). As such, the co-housing constraint is fulfilled and even used as a parameter in the advantage of the design team to structure the building site as well. This design was later on abandoned in favour of the design proposal shown in Figure 4, in which seven towers are grouped in a less visual way, thereby complying to yet other constraints (e.g. sunlight penetration and privacy).

### 2.2 Method of analysis

In the overall design process followed by the considered design team (Figure 2-4), we have selected and studied four particular design sessions, in which a conversation and discussion occurs between the design students and the design teacher. In analysing these four sessions, we used the linkography method outlined above. We used the LINKOgrapher tool [5] to analyse the resulting linkographs. This tool relies on an input spreadsheet file that encodes the distinct design moves, the links between the design moves, and the FBS codes affiliated to all design moves. Using this information, the LINKOgrapher tool not only generates a visual representation of the resulting linkograph, it also makes a set of graphs and calculations based on the linkograph and the FBS codes. These include link index tables, entropy value tables, Markov models and other more general statistics. The results of this study were compared with the results of an interview with the student design team, in order to check the correctness of our conclusions.

### 2.3 Results

Of the four analysed design sessions, two sessions represent an early design phase, one represents a late design phase and one represents the final design presentation. Four linkographs were produced, and they are shown, for reference, in Figure 5. The analytical data that can be retrieved from these linkographs, such as critical moves, link indexes, dynamic models, probability analyses, entropy evolution, and so forth, were then compared over the four sessions in order to expose the impact of parameters and constraints on the design team and the design process. An in-depth linkography analysis of the first session is available in [29]. In the following section, we will document our conclusions regarding the ways in which parameter impact and constraint impact can be noticed at a larger scale, across the diverse design sessions.

## 3 Analysis and discussion

### 3.1 General statistics

Using the LINKOgrapher software, a number of general statistics can be found. These statistics are repeated below for the four design sessions, in chronological order.

## Session 1 – 23 October 2013

451 design moves
977 links
Link Index (LI): 2,17
Issue distribution:

| | | |
|---|---|---|
| R | 74 | 16,4 % |
| F | 26 | 5,8 % |
| Be | 57 | 12,6 % |
| Bs | 200 | 44,3 % |
| S | 85 | 18,8 % |
| D | 9 | 2 % |

## Session 2 – 30 October 2013

616 design moves
1509 links
Link Index (LI): 2,45
Issue distribution:

| | | |
|---|---|---|
| R | 30 | 4,9 % |
| F | 30 | 4,9 % |
| Be | 97 | 15,9 % |
| Bs | 272 | 44,7 % |
| S | 163 | 26,8 % |
| D | 17 | 2,8 % |

## Session 3 – 11 December 2013

1189 design moves
2392 links
Link Index (LI): 2,01
Issue distribution:

| | | |
|---|---|---|
| R | 69 | 6,2 % |
| F | 37 | 3,3 % |
| Be | 126 | 11,3 % |
| Bs | 562 | 50,4 % |
| S | 269 | 24,1 % |
| D | 53 | 4,7 % |

## Session 4 – 18 December 2013

372 design moves
761 links
Link Index (LI): 2,05
Issue distribution:

| | | |
|---|---|---|
| R | 9 | 2,6 % |
| F | 4 | 1,1 % |
| Be | 11 | 3,2 % |
| Bs | 170 | 48,7 % |
| S | 95 | 27,2 % |
| D | 60 | 17,2 % |

First of all, each session has a notably high link index (from 2,01 to 2,45), especially when keeping in mind that Goldschmidt marks a LI value of 0,83 as low and a LI value of 1,73 as high [8]. Following Goldschmidt's interpretation of what constitutes productive design processes (high LI values), the four design sessions were all very productive, and the second session was most productive.

### 3.2 Short analysis of each design session

#### Session 1 – 23 October 2013

The first design session took place after three weeks in the three-month design process. The recorded design conversation dates 23 October 2013 and lasted for about 45 minutes. The transcription of the recorded design protocol can be structured using *design episodes*, segments of activity aimed at reaching a certain goal [34]. In session 1, the following design episodes can be identified:

1 Tower circulation
2 Tower dimensions and volume
3 Parking and deck design
4 Summary

The resulting linkograph (first graph in Figure 5) consists of two clear design episodes concerning the circulation of the towers and the parking and deck design. The overall form of the linkograph shows one big triangle, in which design moves are densely connected but not totally connected, indicating that there are lots of opportunities for good ideas with development [19].

A number of critical moves (CMs) could be identified. This session had a total of 25,5% critical moves of five links or more ($CM^5$) and a total of 8,4% critical moves with seven links or more ($CM^7$). In terms of forelinks, design moves 7, 170, 201, 202, 320 and 322 are most critical. In terms of backlinks, design moves 140, 141, 221, 416 and 448 are most critical. Most of the design moves in terms of forelinks are annotated as Structure (S) and Behaviour derived from Structure (Bs), whereas most of the design moves in terms of backlinks are annotated as Requirements (R) and Behaviour derived from Structure (Bs).

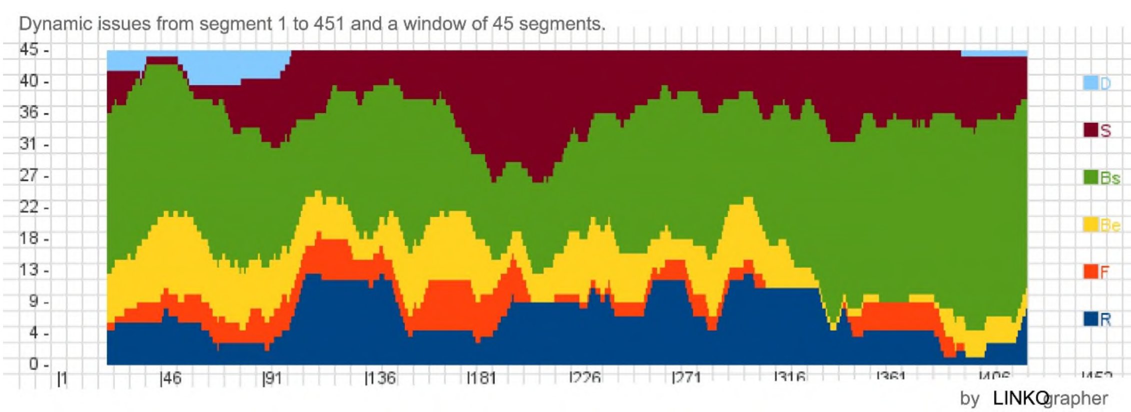


*Figure 6 Dynamic issue distribution of design session 1*

Using the FBS ontology (Figure 1), it is possible to analyse in what ‘character’ the design process proceeds. Namely, the linkograph records not only the sequence of design moves (linear sequences left to right in Figure 5), it also encodes the direct relations between design moves over time, based on content (diagonal links in Figure 5). Each of these design moves is coded according to the six codes in the FBS ontology (Figure 1). In addition, the FBS ontology specifies how a ‘transition’ from one code into another should be interpreted. For instance, a transition from an F-encoded design move (Function) to a Be-encoded design move (Expected Behaviour), can be interpreted as a process of ‘Formulation’. This can be done for the linear sequence of design moves (linear sequences left to right in Figure 5), resulting in an overview of dynamic processes in a *syntactic* form, or it can be done for the encoded links of the linkograph (diagonal links in Figure 5), resulting in dynamic processes in a *semantic* form.

Figure 6 depicts the dynamic issue distribution of the first design session, as it is generated by the LINKOgrapher software. From this graph, the share of each design issue can be obtained at each moment of the design conversation (colour legend right in Figure 6). At any point in time (horizontal axis), a certain ‘window’ of design moves is considered (in the case of Figure 6, 45 design moves are considered), and an impression is given of how many of these design moves are encoded as D, S, Be, Bs, F, and R.

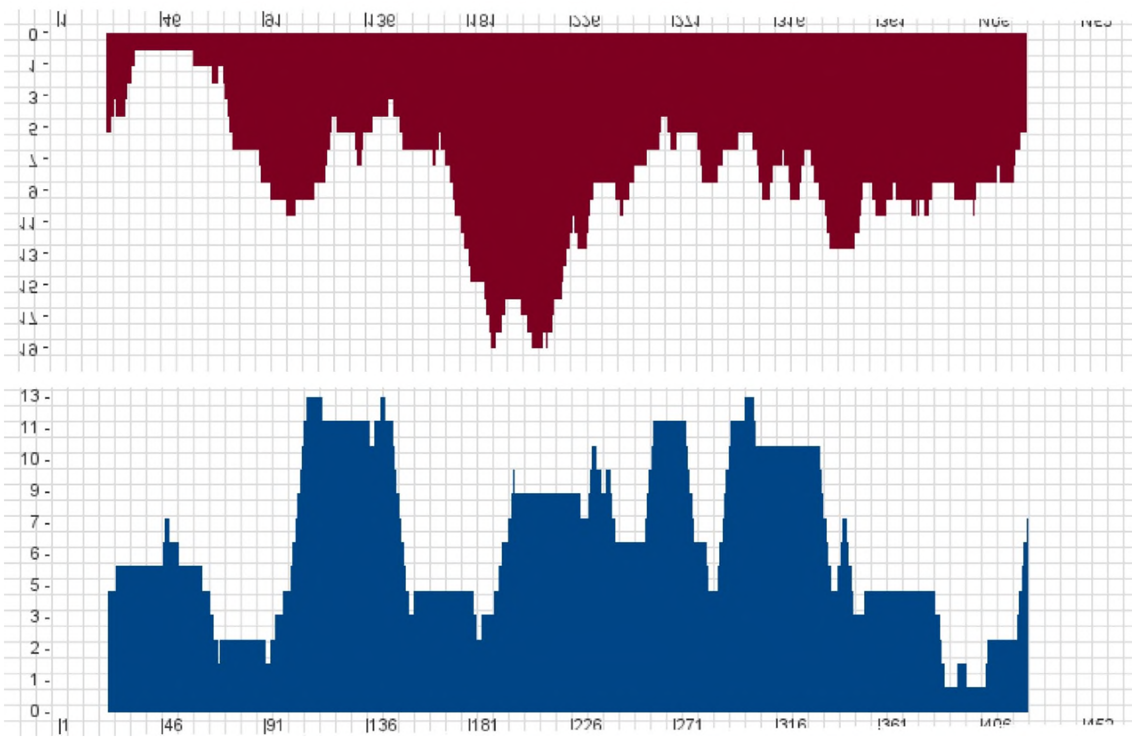


*Figure 7 The saw-tooth outline followed by the design moves annotated as Structure (S – red) and the design moves annotated as Requirements (R - bottom) in design session 1*

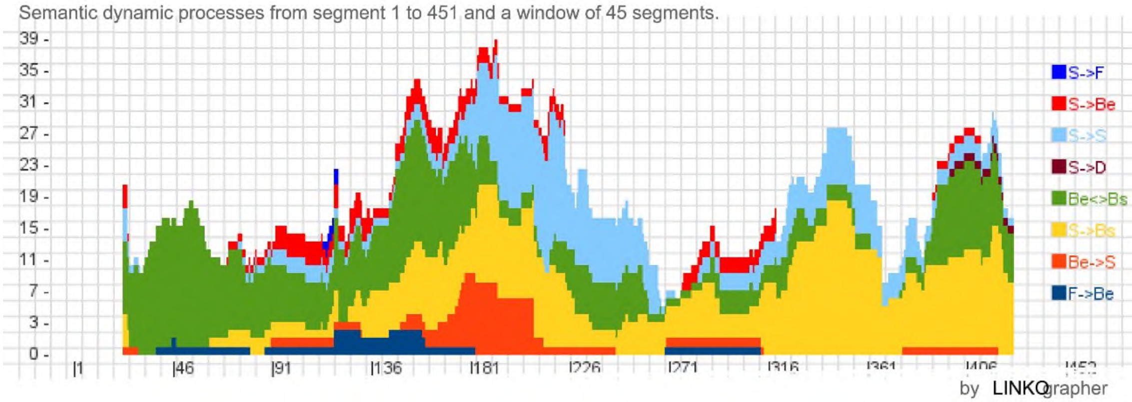


*Figure 8 The semantic dynamic process distribution graph for design session 1, as output by the LINKOgrapher software, shows four easily distinguishable peaks*

From the dynamic issue distribution in Figure 6, one can see that the usage of documentation (D) is limited towards the beginning and the end of the design session. In addition, one can clearly notice the large share of design moves annotated as Behaviour derived from Structure (Bs) towards the end of the design session, which indicates that the main decisions (Structure) about the design proposed in that particular design session are set and understood, and focus is put on the evaluation of the effects of these decisions. In this case, there is little counterbalance from design moves annotated as Expected Behaviour (Be), which implies that this evaluation is not really taking into account many of the originally expected behaviours.

A third conclusion that can be drawn from the same graph, but which is even better displayed in Figure 7, is that the design moves annotated as Structure (S – red in Figure 7) follow an outline that is inverse to the outline followed by the design moves annotated as Requirements (R – blue in Figure 7). This indicates that a surge of Requirement-focused design moves (R) is typically followed by a surge in Structure-focused design moves (S). As in any saw-tooth diagram, it is not entirely clear which is the cause and which is the result. It might be logical to assume that the surge of Structure-focused design moves (S) respond to the requirements that were elicited in the surge of Requirement-focused design moves (R). However, it appears from the content of the design session that new requirements were pointed out *because* they appeared to be unattended in the Structure-focused design moves. For example, only after the design students presented their idea of building a separate tower for circulation, including lift shafts and staircases separate from the actual housing units, important requirements emerged regarding fire safety and evacuation measures.

The dynamic process distribution graph in Figure 8 is similar to the graph in Figure 6, only focusing on the arrows of the FBS ontology (see Figure 1) distributed over the session, instead of the distribution of the actual FBS codes only. Figure 8 shows the *semantic* dynamic process distribution as output by the LINKOgrapher software.

Two clear conclusions can be made from this graph. First of all, there is one large peak of processes in the centre of the graph. This large peak coincides with the two largest inverse peaks in the saw-tooth diagram displayed in Figure 7. This particular portion of the design session deals with the implantation of the tower in the overall site and its relations with the surrounding urban context. As can be seen in Figure 8, this peak starts with a small peak in formulation processes (F->Be) and evaluation processes (Be<->Bs), followed by a notably increasing share in synthesis processes (Be->S) and finally also in Reformulation I (S->S). This peak thus appears to represent a highly productive process that nicely follows the process that was in mind of the developers of the FBS ontology (Figure 1).

A second conclusion that can be drawn from Figure 8, is the clear focus on evaluation (Be<->Bs – green in Figure 8) and analysis (S->Bs – yellow in Figure 8). In particular, the leftmost ellipse in Figure 8 displays an almost complete focus on evaluation (Be<>Bs), indicating that this part of the design process mainly focused on indicating whether or not expected behaviour (Be) was met by behaviour derived from structure (Bs). On the other hand, the rightmost ellipses in Figure 8 focus more on analysis. When considering the actual content of the design session, it appears that this part of the design session focused on all the behaviour generated by particular decisions made in the design (Structure) that were not necessarily taken into account at the start of the design process (Be).


*Figure 9 The forelink entropy distribution shows two peaks of higher entropy and thus higher productivity*

The availability of the links between the design moves allows to calculate entropy over the entire linkograph or over portions of the linkograph. Hence it is also possible to generate a 'windowed' graph of entropy evolution over the entire linkograph. Kan and Gero [17] distinguish here between forelink entropy, backlink entropy and horizonlink entropy. Forelink entropy is hereby understood to measure the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. And horizonlink entropy measures the opportunities relating to cohesiveness and incubation [18].

Figure 9 shows the forelink entropy evolution over the entire design process. The backlink entropy evolution follows more or less the same outline in this design session. The graph indicates that there are two peaks in the entropy, namely from design move 114 to 189 and from design move 314 to 366. According to Kan and Gero [17-18], these parts of the design process have the highest design productivity, primarily because they exhibit the best opportunities for new creations and initiations (forelink entropy). This graph is clearly compatible with the graph in Figure 8.

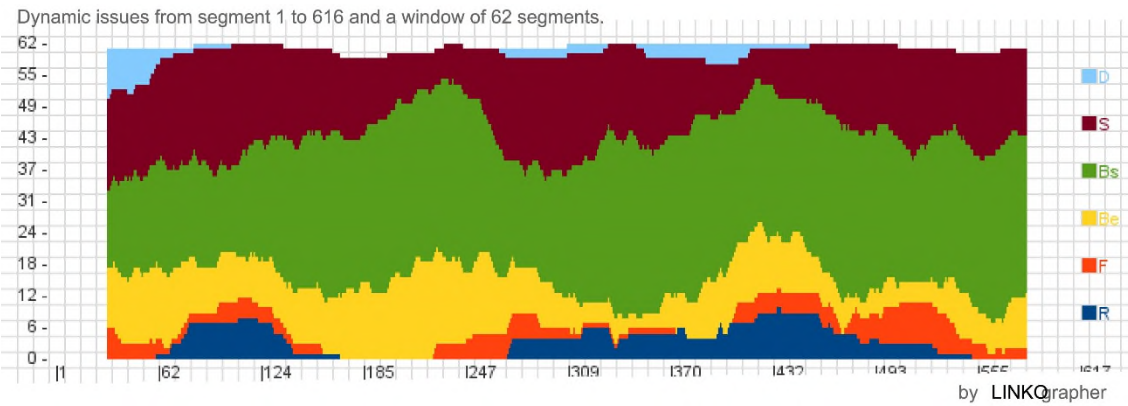


*Figure 10 Dynamic issue distribution of design session 2*

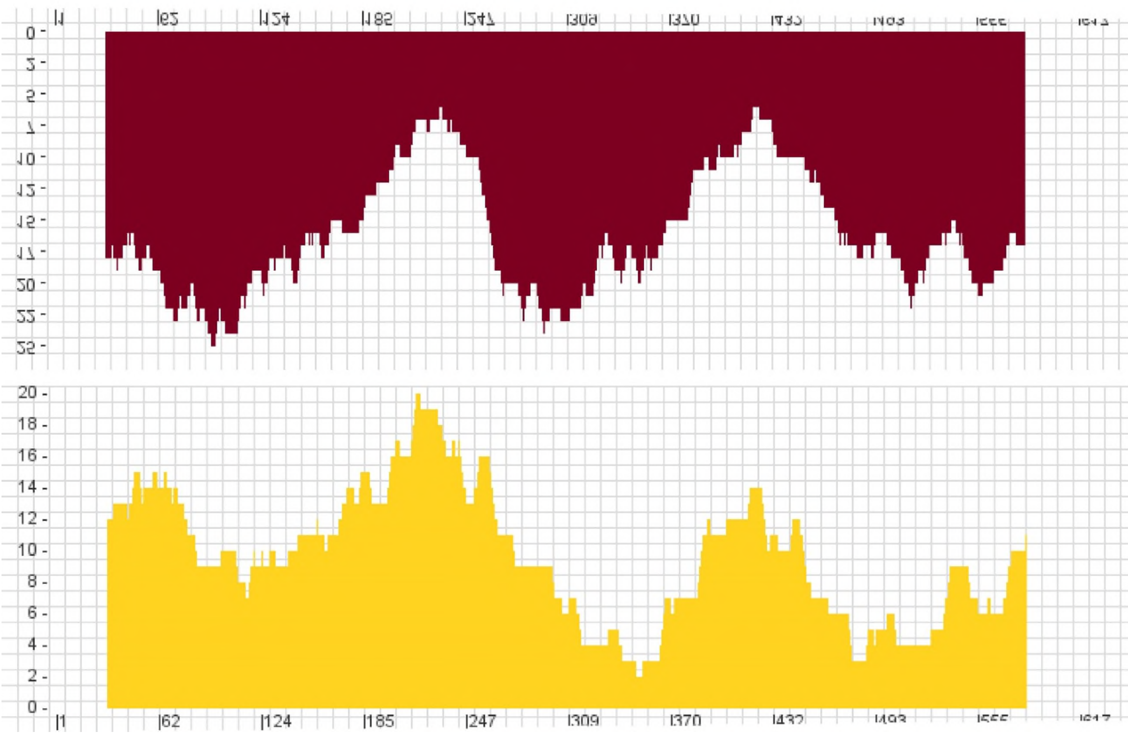


*Figure 11 The saw-tooth outline followed by the design moves annotated as Structure (S – red) and the design moves annotated as Expected Behaviour (Be) in design session 2*

**Session 2 – 30 October 2013**

The second feedback session took place on 30 October 2013 and lasted for about 1 hour. This session focused more closely on the co-housing concept that was to be developed in diverse scales (unit scale, co-housing community scale, tower scale, tower group scale, environment scale). This served as a major constraint to further design the different towers and co-housing units. For this design session, the following design episodes can be identified:

1 Co-housing concept
2 Duplex principles
3 Shaping the façade
4 Structural design
5 Urban context design
6 Façade and roof top

The resulting linkograph of session 2 is presented as the second graph in Figure 5. The linkograph is highly similar to the linkograph of the first session, in the sense that also this second linkograph shows one big triangle with a dense, yet not fully connected, network of links. So, also for this design session, a high level of design productivity can be anticipated.

The distinction between episode 2 and 3 is less clearly present in the shape of the linkograph. These two episodes, however, do have different subjects and goals, namely the elaboration of the duplex principles and the shape of the façade. Still, the duplex principles exert a strong influence on the shape of the façade and, as a result, both design episodes appear to be heavily interlinked (left of 2nd linkograph in Figure 5).

Session 2 had a total of 27% $CM^5$ and 9,6% $CM^7$. This is higher than in the first design session, indicating a more productive design process. The most critical moves in terms of forelinks are annotated as Structure (S), whereas the most critical moves in terms of backlinks are annotated as Bs or Be, indicating an evaluative or analytic nature. The requirement issue thus seems to be of less importance in session 2.

Figure 10 shows the dynamic FBS issue distribution for design session 2. This graph is similar to the graph of the dynamic issue distribution of design session 1 (Figure 6). The main difference is that design moves annotated as requirements (R) are a lot scarcer compared to the first design session (below in Figure 10) and design moves annotated as documents (D) surface in the middle of the design process as well. The Documentation (D) at the outset of the design process is related to the content of the first two design episodes of this session: it shows the design proposals regarding the co-housing concept and the duplex principles that were central in this design session. The Documentation (D) in the middle of the design process is related to the content of the fifth design episode, which focuses on the urban context. This part of the design process deals with content on an entirely different scale, hence, it makes sense that it relates to different documents.

Also in this design session, surges of Requirement-focused design moves (R) are followed by surges of Structure-focused design moves (S). However, in this design session, one can see an intermediary surge also of design moves annotated as expected behaviour (Be). The saw-tooth behaviour that we noticed in Figure 7 is now even better perceivable between Be- and S-annotated design moves (Figure 11).

Figure 12 shows the semantic dynamic process distribution as output by the LINKOgrapher software, which is equivalent to the graph displayed in Figure 8. The content of the graph is notably different, however. Note that the vertical axis in Figure 12 counts to 92, as opposed to the vertical axis in Figure 8, which counts only to 39. The horizontal axis counts only 100 design moves more. The number of semantically recognised processes (FBS processes taking place over the links of the linkograph) is thus overall considerably higher.

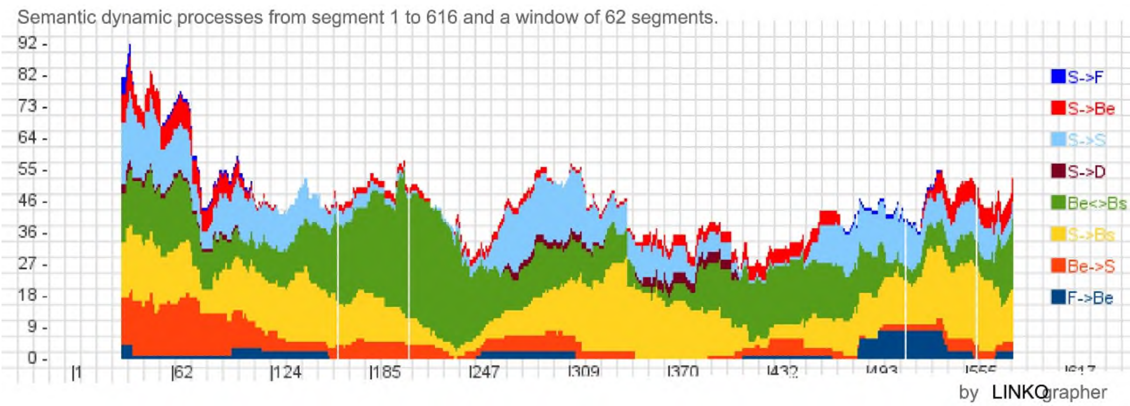


*Figure 12 The semantic dynamic process distribution graph for design session 2, as output by the LINKOgrapher software, is considerably different from the graph for design session 1 (Figure 8)*

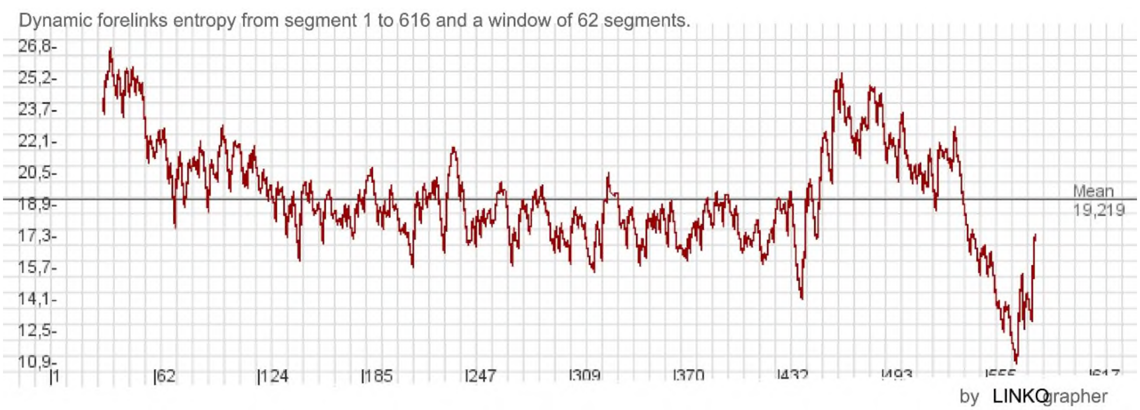


*Figure 13 The forelink entropy distribution of design session 2 shows one peak of higher entropy at the start, and one towards the end, implying idea generation opportunities in terms of new creations or initiations at the start and at the end*

In terms of the content of this graph, one can see a clear focus on synthesis (Be->S – orange in Figure 12) at the outset of the design session, compared to the remainder of the design session. Between design move 124 and 230, a high amount of evaluation (Be<->Bs – green in Figure 12) takes place. When combining this with what we see in Figure 10 and 11, this can be explained as a design session in which the design students start from their documents (Figure 10) with explaining how they came to their current design status

(Be->S in Figure 12). This is then evaluated during the discussion with the design teacher (green area in Figure 12). The design moves between move 247 and 430, as well as between move 460 and 570, are entirely different, as they consist primarily of analysis (S->Bs – yellow in Figure 12) and reformulation I (S->S – light blue in Figure 12). These two parts of the design process are the parts where the conversation between design students and design teacher focus on the structural design (design episode 4) and on the urban context design (design episode 5). In these design episodes, the design is incessantly evaluated and modified.

The forelink entropy distribution for design session is quite different as well from the forelink entropy distribution in design session 1 (Figure 13 versus 9). First of all, the mean entropy value 19,2 is higher (13,4 in session 1). In addition, there are less high peaks and less low valleys in the graph, indicating that entropy remains quite high during the entire session. Small peaks can be found at the start and at the end of the graph.

**Session 3 – 11 December 2013**

The third session took place towards the end of the three-month design process and thus had a lot more context and detail. This session took place on 11 December 2013 and was the longest design session of all analysed sessions, with a total of 2 hours and 10 minutes. This amount of time was necessary to cover the detail present in the design at that moment. Figure 14 gives an indication of that amount of detail for the floor plans.


*Figure 14 One of the floor plans of the towers as made by the students in design session 3*

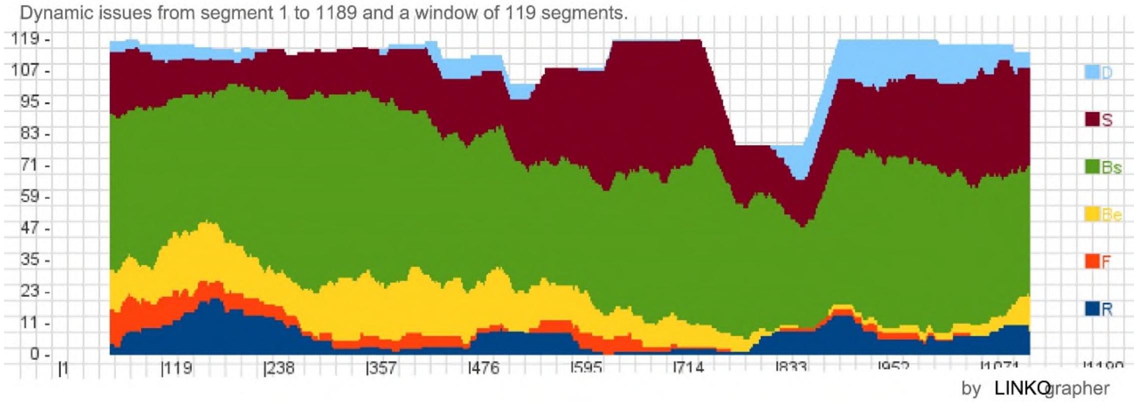


*Figure 15 The dynamic issue distribution of design session 3 has a clear focus on final evaluations, the main structure of the design structure and the documentation*

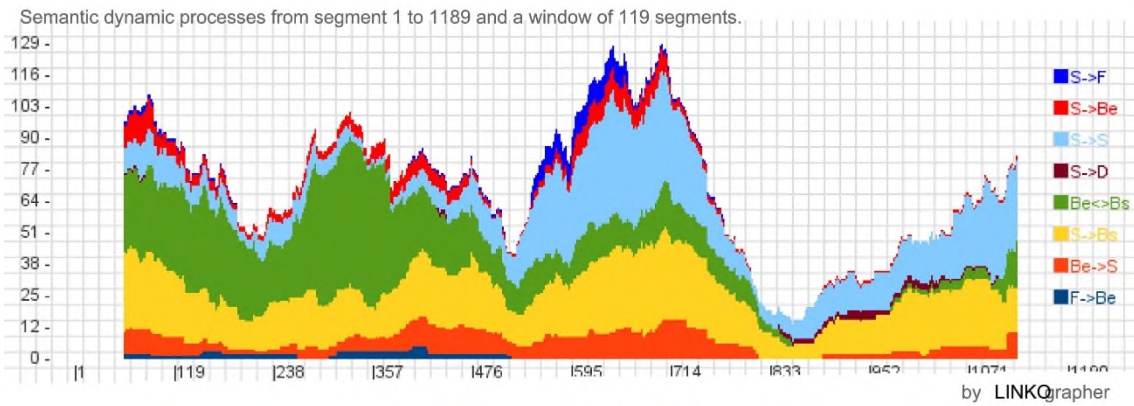


*Figure 16 The semantic dynamic process distribution of design session 3*

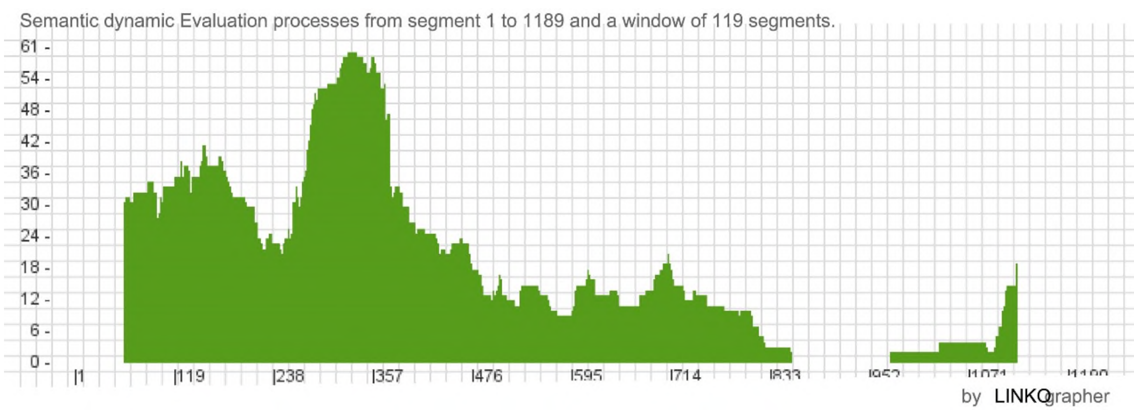


*Figure 17 The semantic dynamic process distribution of evaluation processes in design session 3*

Six design episodes could be outlined, splitting the complete design session as following:

1 Privacy
2 Detailing and performance
3 Building structure
4 Calculation of column section
5 Ground and underground floors
6 Professional activities in towers

The first design episode handled privacy issues still present in the design and needing to be resolved. The second design episode handled about the detailing and the material choice for the walls and columns and their correspondence to the constraints or requirements that were initially set (acoustics, fire safety, etc.). Design episode 3 entirely dealt with the structural concepts for the towers, followed by an explicit calculation episode for one of the columns in the towers. In the fifth episode, the lower floor levels were discussed, as they included extra facilities (parking, shops, professional activities, etc.). The last episode then dealt with the ways in which common / public zones in the buildings might be usable for professional activities (bed and breakfast, office rental, and so forth).

Session 3 only has 7,65% $CM^5$ and 3,45% $CM^7$. The amount of critical design moves is considerably lower than in the first two sessions, indicating less design productivity, if we follow Goldschmidt's recommendation to use the CM measure as an indication of design productivity [8,10]. This can also be seen in the linkograph diagram as it is presented in Figure 5 (third diagram from the top). This is not a single triangle with a rather dense, but not totally connected network of links. Rather, it can be classified as a number of separate episodes (local triangles), each of them somewhat related to the other episodes, yet still handling entirely different topics (structure, function, privacy, etc.).

The most critical moves in terms of forelinks are annotated as Requirement (R) and Structure (S), whereas the most critical moves in terms of backlinks are annotated as Behaviour derived from Structure (Bs) and Expected Behaviour (Be). This makes sense when considering the content of the design session, as the session went into very concrete detail and evaluated (Bs and Be) how the buildings (S) functioned (material choice, structural load-bearing capacities, usage of spaces, privacy, and so forth) in close relation to the given requirements (R).

Figure 15 shows the dynamic issue distribution of design session 3. This is the last design session before the actual presentation, which is design session 4. Hence, one can see that design moves focusing on documentation (D) are more prominently present, with a clear peak towards the end of the design session. The peak towards the end occurs in design episodes 5 and 6, which focus on the ground floors of the towers and the professions that could take place there (day care units, shops). Furthermore, Figure 15 shows a focus on expected behaviour at the outset of the design session (yellow in Figure 15), followed by a focus on structure (S – red-brown in Figure 15) and documentation (light blue in Figure 15) towards the end. The saw-tooth profile is far less visible in this design session, indicating a clear focus on end results, synthesis and documentation, contrary to what happened in the initial two design sessions.

The semantic dynamic processes distribution of design session 3 looks again quite different from the distributions of session 1 and 2. In this case, three peaks can be distinguished in the first part of the design process. This is followed by a significant decline around design move 800, after which a steady increase follows again until the end of the design session.

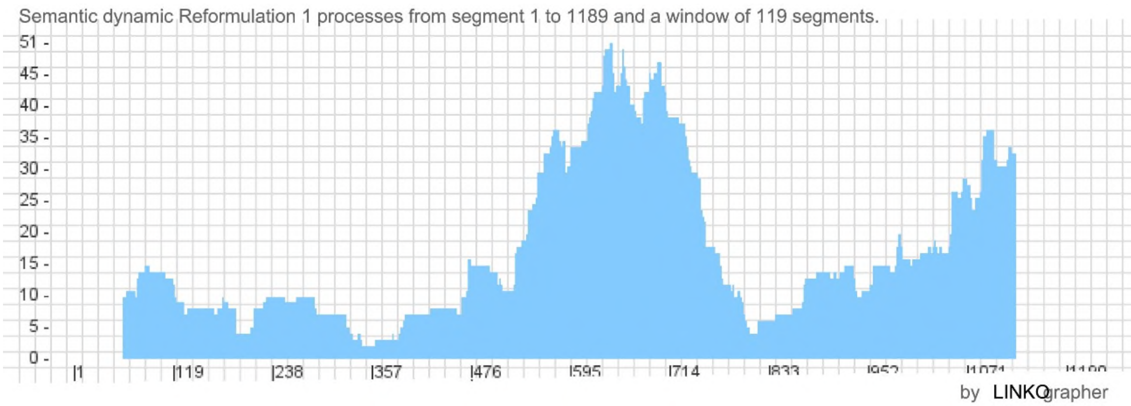


*Figure 18 The semantic dynamic process distribution of reformulation I processes in design session 3*

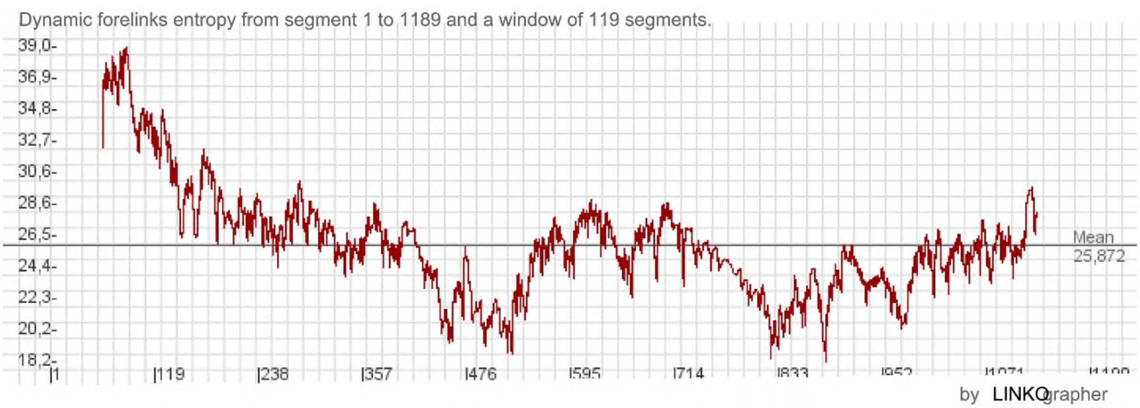


*Figure 19 The forelink entropy evolution in design session 3 peaks at the start and maintains a rather flat shape in the remainder of the design session*

The valley in this graph (around design move 800) coincides with a discussion about the building structure (design episode 3), in which the design teacher urged the students to calculate the load on the columns in order to properly predict their size. In this episode, the focus was on the explanation of this calculation method, which had little to no references to other design moves. The two peaks before that (moves 230-480 and moves 500-750) are caused by peaks in evaluation (Be<->Bs – green in Figure 16) and in reformulation I (S->S – light blue in Figure 16). We repeat these two peaks separately in Figure 17 and 18 to give a better impression of this feature of the design session.

The peak in evaluative processes coincides with an evaluation of the building structure in relation to the plans of the apartments (Figure 14). The rather large spans executed in wood imply the use of large beams that will surely be visible in the interior of the apartments and they imply the use of cross-laminated timber structures. It appeared that this was not taken into account in the presented design, indicating that the students overlooked important aspects that would shape the look and feel of the apartment units.

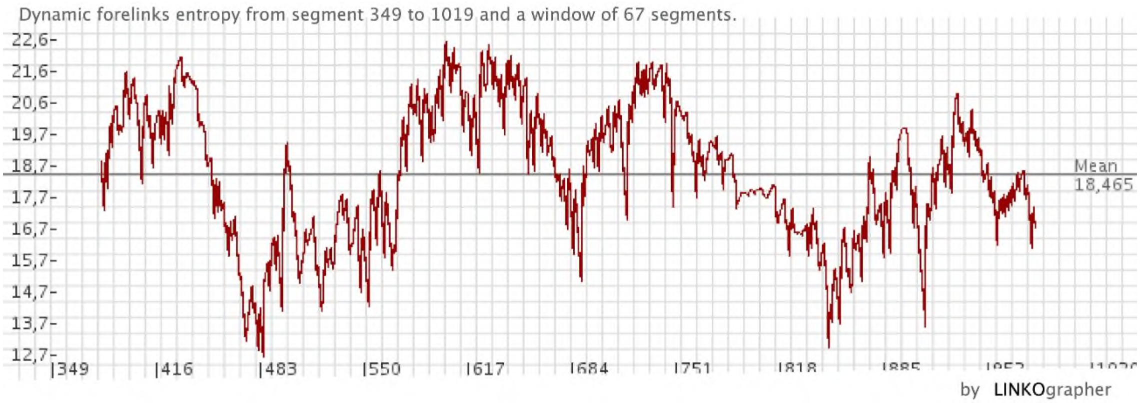


*Figure 20 The forelink entropy evolution in design moves 345 to 1019 shows a peak in the middle that coincides with the middle peak in Figure 16*

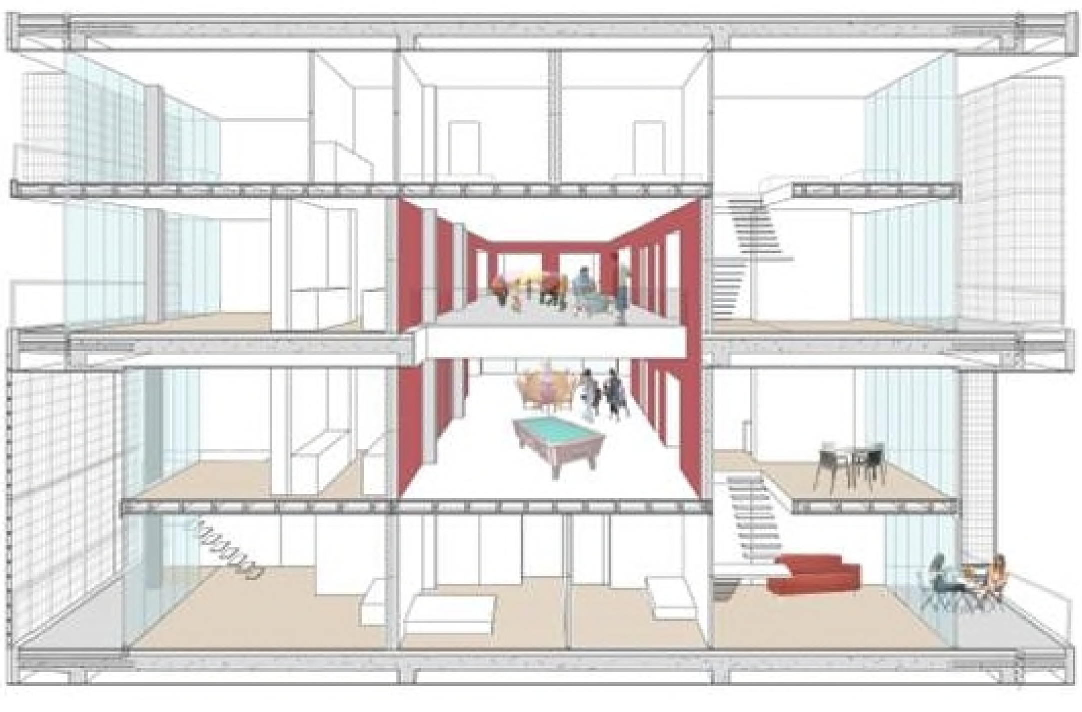

*Figure 21 A key overview section providing an impression of how one of the co-housing communities is given shape*

The peak in reformulation I processes, as displayed in Figure 18, then contains literally a reformulation and a rethinking of that building structure, which is key to the entire design and thus also omnipresent in the graph in Figure 16. By moving columns and changing span directions, the design teacher and design students attempted to reduce span lengths and limit the impact on the floor plan design of the apartments.

When considering the forelink entropy distribution again (Figure 19), one can see that the biggest opportunities for idea generation (peak in the graph) are again found at the beginning of the session, when discussing the exterior walkabout and the interior configuration of the apartments (design session 1).

The two valleys in the graph (around design move 476 and 833) indicate that the lowest design productivity occurs when discussing an internet site of cross-laminated wooden beams and the calculation of column dimensions. These valleys also coincide with the two last valleys in the dynamic process distribution in Figure 16. Note also that the entropy evolution graph looks a bit different if we specifically zoom in on the peak of design processes as it occurs in Figure 16 between design move 500 and 750 (see also Figure 18). This is shown in Figure 20: two peaks of higher entropy can more easily be recognised in this part of the design session.

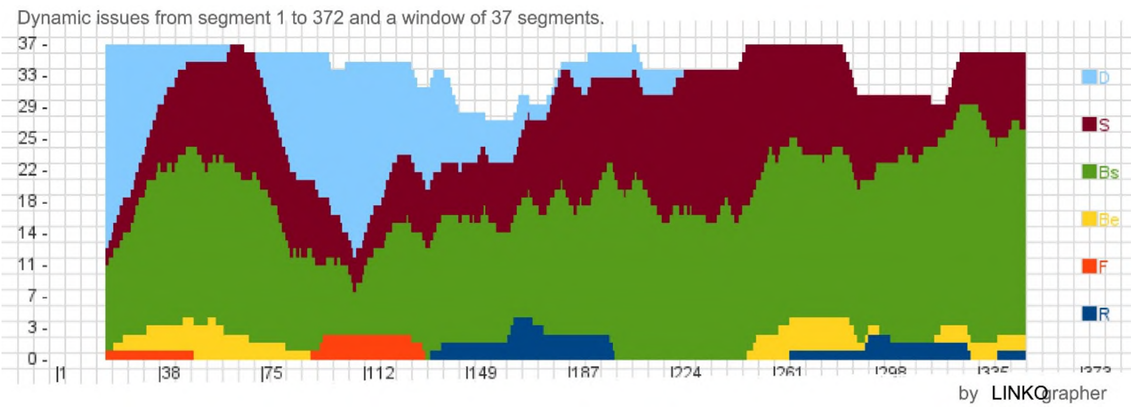


*Figure 22 The dynamic issue distribution of design session 4 has a clear focus documentation*

## Session 4 – 18 December 2013

The last session that was analysed, dates 18 December 2013 and lasted about 43 minutes. The nature of this design session is entirely different from the other three, because it represents the final design presentation in front of a four-person jury. This implies that further changes to the design can only be mentioned as missed opportunities; they cannot really be considered as valid options for further changing the design. Upon mentioning these missed opportunities, the discussion thus simply stops and goes to any of the other features of the final design that is presented (Figure 21).

This is clearly reflected in the linkograph obtained for this design session (bottom graph in Figure 5). It is entirely different from the other three linkographs. It has a 'saw-tooth' look, its major feature being the presence of a relatively large number of smaller triangles instead of one major triangle. Design moves are thus often related to directly preceding design moves, which indicates a sequentially *progressing* process rather than a *developing* process [19]. This makes sense, as the final design presentation is meant to include sequentially progressing evaluation rather than design development. This is apparently also retrievable in the linkograph structure.

Session 4 has 17,5% CM[5] and 3,5% CM[7], which is somewhat comparable to session 3 (less productivity). The most critical moves in terms of forelinks have very diverse annotations (S, Bs, Be, F, R). The most critical moves in terms of backlinks are all evaluative of kind (Bs and Be), which makes sense considering the evaluative nature of this session.

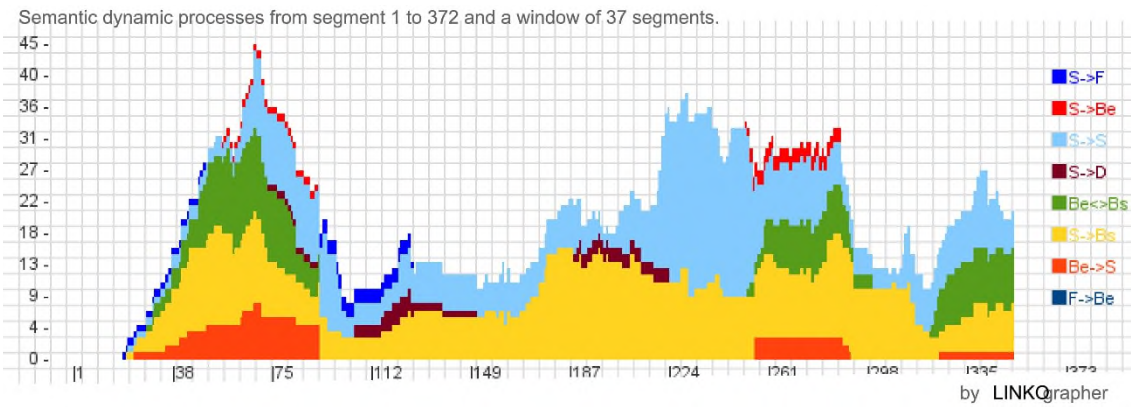


*Figure 23 The dynamic processes distribution of design session 4 consists mainly of analysis (S->Bs – yellow) and reformulation I (S->S – light blue), hence indicating the character of final presentation*

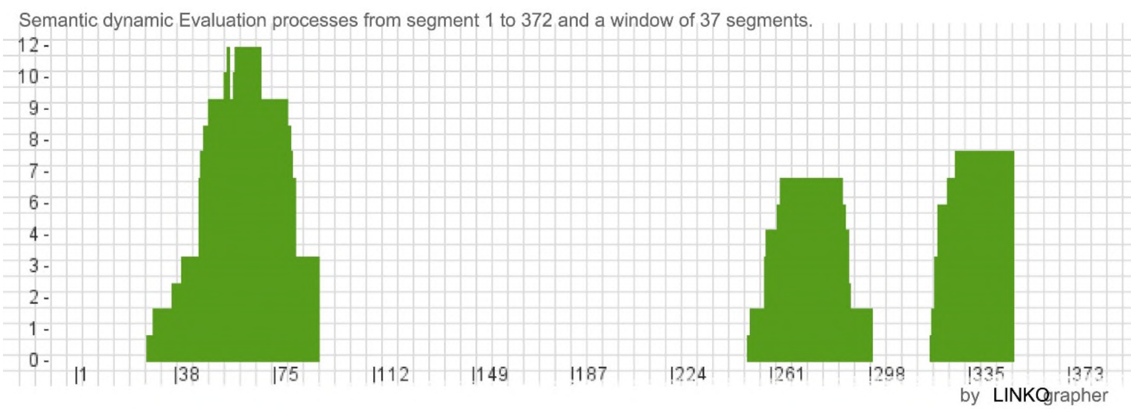


*Figure 24 Three distinct peaks of evaluation (Be<->Bs) take place throughout design session 4*

Figure 22 shows the dynamic issue distribution of design session 4. Most remarkable in this graph is the presence of two peaks of design moves annotated as Documentation (D) in the start of the design session. Moreover, each peak is followed by a peak of design moves annotated as Structure (S) and Behaviour derived from Structure (Bs). The two peaks in Documentation-related design moves concern the presentation of the design for the ground and underground floors (first peak) and the design for the towers (second peak). Also, the share of design moves annotated as Requirements (R), Function (F) and Expected Behaviour (Be) is notably smaller throughout the entire design session.

The semantic dynamic processes distribution of design session 4 is given in Figure 23. The peaks of Documentation-related design moves (D) in Figure 22 coincide with strong valleys in the dynamic processes distribution in Figure 23. Because the presentation of the design consisted nearly entirely of pointing to existing documents, little design processes took place. Furthermore, one can clearly notice the major share taken by analysis (S->Bs) and reformulation I (S->S). In this feature, one can notice the difference between a design session focusing on final presentation and a regular design session.

There is one major peak in reformulation I (S->S) around design move 224. This peak represents an important reformulation of a design decision by the design teachers. The students presented the building structure as a concrete frame which was to be filled with ‘duplex boxes’ in wood. The wooden floors in the duplexes allow for great flexibility, because they could be adapted at will and the concrete floors acoustically separated the different apartments. However, the same system was applied to the duplex co-housing space, which was situated one level higher or lower than the duplex apartments. This caused acoustical problems, because above and underneath the co-housing space, where it could be noisy, was a wooden instead of a concrete floor. The design teachers hence justly commented that the wooden and concrete floors should have been switched in the inner core of the towers, which comes across in Figure 23 as a reformulation of the design structure.

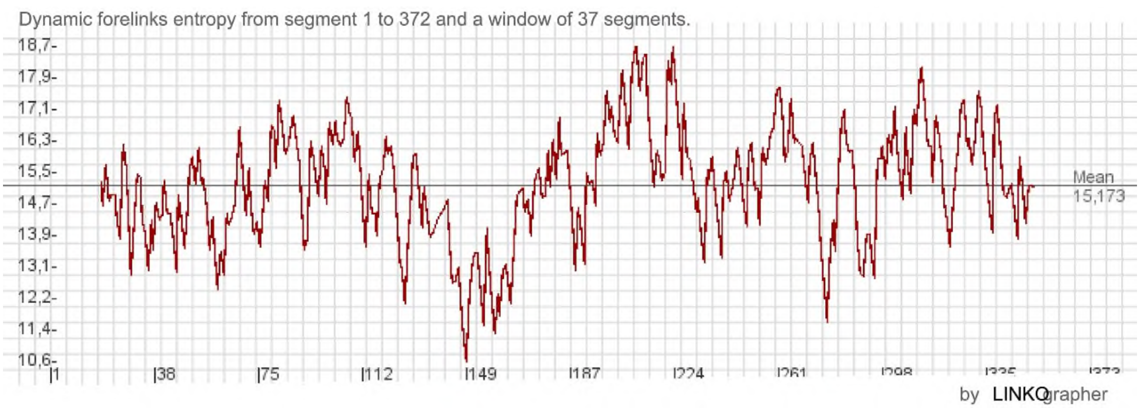


*Figure 25 The entropy evolution in design session 4*

Lastly, evaluation of Expected Behaviour against Behaviour derived from Structure (Be<->Bs) takes place at three distinct places in the design session (Figure 24). From the left to the right, the peaks correspond to (1) an evaluation of light penetration in the underground parking and the conception of the foundation; (2) an evaluation of the sustainability of the building; and (3) an evaluation of the HVAC installations in the building.

Finally, the entropy distribution, which is displayed in Figure 25, shows a rather unstructured profile. The average entropy is rather high (15,1). This would indicate that there are quite some opportunities for initiation and creation of ideas overall. The most distinct peak in Figure 25 takes place around design moves 190-220, which is also the period in the design session that shows a lot of analysis (S->Bs), according to Figure 23. Indeed, this span of design moves in the design session resulted in the design team to reconsider and reformulate the wooden-concrete framing structure used for the towers. Hence, the design moves from 190 to 220 resulted in new ideas and alternative conceptions

### 3.3 Analysis spanning all four design sessions

Requirements have been tracked throughout all four sessions using the Requirement (R) notation of the FBS coding schema. Their share in all design sessions is displayed in Figure 26, together with the shares of the other annotation codes of the FBS ontology. The requirements tend to refer to the constraints that were originally present in the design brief, and they are thus of particular importance here. In percentages, 16,4% of the design moves in session 1 was related to requirements, contrasting significantly with the values for the other sessions (4,9%; 6,2%; 2,6% - see leftmost portion of the histogram in Figure 26). In the discussion of all four design sessions, we have indeed seen little emphasis on requirements. It appears that design requirements were mainly considered at the beginning of the design process, when still relating closely to the design brief.

Later design stages are considerably more occupied by design moves that are annotated as ‘Structure (S)’, ‘Expected Behaviour (Be)’, and ‘Behaviour derived from Structure (Bs)’. It thus appears that design constraints are communicated and considered from the design brief, after which they are considered as ‘implicitly known givens’ and make place for analysis and evaluation. Only to a limited extent, requirements are reconsidered in the later stages of the design process. Also the design moves that are annotated as ‘Function (F)’ decrease in share (5,8% -> ; 4,9% -> 3,3% -> 1,1%), indicating that the functions and overall program of the design tends to gradually stabilise during the design process, which also explains the decreasing need to return to design requirements.

The histogram in Figure 26 also clearly shows the difference between the intermediate design sessions and the final presentation session. The presentation session has considerably less design moves annotated as Expected Behaviour (Be), let alone Requirement (R) or Function (F), and has considerably more design moves annotated as Documentation (D).

### 3.4 Evaluation through student interview

The interview with the student designers confirmed the above findings, indicating that the quantitative assessment with the linkographs is appropriate. The student designers additionally indicated that they had a difficult start because of the large number of constraints and requirements that were posed. They indicated that this gradually improved because more building features got ‘fixed’, thereby addressing a number of constraints that did not have to be considered any more as long as these building features remained fixed. So the problem space narrowed in scope because partial solutions got fixed and the solution space narrowed in scope as well, thereby indicating the co-evolution of problem and solution in practice.

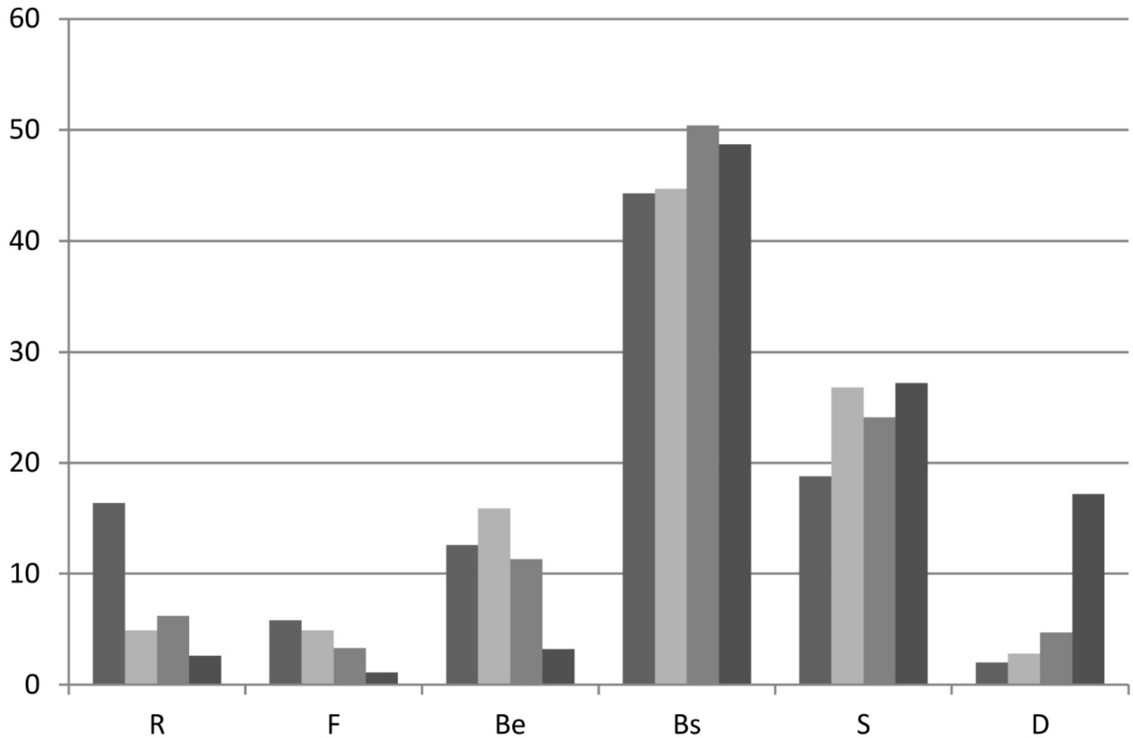


*Figure 26 Bar graph of the shares (%) of the different design move annotations in FBS over the four feedback sessions. For each FBS code, four bars represent session 1-4 (chronological from left to right)*

## 4 Conclusion

In this paper, we have looked at the impact of constraints on the architectural design process and the way(s) in which they are dealt with by designers, thereby relying on a use case in a student design studio. As requirements have an important influence on the decision-making processes in architectural design, it is important to know how they are handled in daily design environments. We therefore tried to formulate answers on a number of questions posed at the beginning of this paper:

- Are constraints in architectural design considered to be limitative (constraining), or are they key reference points in a variety of parametric possibilities?
- Are constraints omnipresent during the design process or are they considered only until they have been 'resolved'?
- Does the set of requirements change during the design process?
- Which parameters are chosen by designers to reply to a specific design situation with a number of given constraints?
- Where does parametric freedom and parametric creativity come from?

In order to find an answer on these research questions and thus to assess the role of constraints and parameters in the design process, we did not only look into available answers in the literature (section 2), we also looked into a specific design use case, in which a design team of two architectural design students designed in reply to a specific design brief containing a particularly high number of constraints. These students went through a 3-month design process and returned at regular interviews to get feedback from the design teacher, in which an evaluation was made of the extent to which the design answered the many requirements in the design brief.

In our study, four of those evaluation sessions were analysed using the linkography method. We consider these sessions as design sessions, because the design typically shifts considerably during these sessions based on the input given by design teachers and the resulting discussions. We used linkography as a method for analysing these four sessions, because it allows to obtain a more quantitative assessment of the design process. The linkography method gave a detailed insight in the way in which each of the design sessions progressed, thereby giving insight in general metrics and statistics about the session, about the entropy evolution and thus possibilities for idea emergence, and about the overall structure and characteristics of the design process. Using the FBS ontology, it was possible to evaluate on what basis ideas emerge and decisions are taken. From this overall analysis, we come to the following conclusions regarding our initial research questions.

- *Are constraints in architectural design considered to be limitative (constraining), or are they key reference points in a variety of parametric possibilities?*
  Constraints can be considered limitative, as they tend to allow only a limited number of design alternatives in order to address them. Yet, they are also key reference points for an architectural designer, in the sense that, once a number of constraints are addressed and the design solution gets clearer and more fixed, the problem space becomes narrower and allows for an increased parametric creativity in the remainder of the problem/solution space.

- *Are constraints omnipresent during the design process or are they considered only until they have been 'resolved'?*
  The linkographs showed that constraints tend to be explicitly present mainly at the beginning of the design process (design brief). As they are addressed one after the other, the design solution is gradually refined and requirements tend to be less explicitly present. They remain (implicitly) present though when making design moves that are function- (F), structure- (S), or behaviour-related. In addition, new constraints (requirements) often also (re-)surface during the design process when particular decisions are made (Structure) that clearly neglect particular unconsidered requirements. This typically results in unexpected Behaviour derived from Structure (Bs) and then reformulation of structure (S->). This occurs in almost each design session of our study. In design session 1, it happened, for example, around design move 150 to 260 (see Figure 8), when a lot of synthesis (Be->S) was followed by reformulation I (S->S) for the implantation of the tower in the urban context. Figure 7 also clearly displays the saw-tooth (action-reaction) profile of design moves annotated as Requirements (R) and Structure (S). Design session 2 has a similar saw-tooth profile (Figure 11) of Structure (S) versus Expected Behaviour (Be), which is often closely related to requirements as well. A similar feature can be recognised in design session 3 when looking at the graphs in Figure 17 and 18. These show a peak in evaluation processes (Be<->Bs), followed by a peak in reformulation I processes (S->S), in order to take into account a practical structural column-bearing system. Also design session 4 has a considerable focus on

requirements (R), however, in this case only to find out whether or not they are met in the final design (see analysis processes S->Bs and reformulation I processes in Figure 22).

- *Where does parametric freedom and parametric creativity come from?*
  If there would not be any constraints, the problem space would be highly under-constrained, leaving all possible parametric options open. As a result, it would be very hard to make any decisions in such a context. What we saw in the use case design process, is that, at every consecutive design situation, a manageable number of constraints is selected by the designers from the virtually unlimited number of constraints present from the design brief. This constraint set deliberately leaves open a useful number of parameters, allowing for the desired level of parametric freedom and parametric creativity. Note that, at evaluation time, it often occurs that new constraints pop up (see previous point) from the perspective of the evaluators (in this case the design teachers), thereby shifting the design focus in alternative directions.

The current work gives an impression of how parameters and constraints affect design processes. Future work, however, could further improve and consolidate this impression by showing how designers pick the desired set of constraints to impose on each specific design situation. This is of high importance as this chosen set of constraints defines the room for parametric freedom and creativity. It is assumed that analogical reasoning will be involved in making this selection. Supposedly, there will also be differences between designers in setting this scope, with certain designers preferring a rather constrained and strict design solution space and other designers preferring a highly open design solution space.

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International Journal of Design Sciences and Technology
Design Sciences, Advanced Technologies and Design Innovations
Towards a better, stronger and sustainable built environment

## Aims and scope

Today's design strongly seeks ways to change itself into a more competitive and innovative discipline taking advantage of the emerging advanced technologies as well as evolution of design research disciplines with their profound effects on emerging design theories, methods and techniques. A number of reform programmes have been initiated by national governments, research institutes, universities and design practices. Although the objectives of different reform programmes show many more differences than commonalities, they all agree that the adoption of advanced information, communication and knowledge technologies is a key enabler for achieving the long-term objectives of these programmes and thus providing the basis for a better, stronger and sustainable future for all design disciplines. The term sustainability - in its environmental usage - refers to the conservation of the natural environment and resources for future generations. The application of sustainability refers to approaches such as Green Design, Sustainable Architecture etc. The concept of sustainability in design has evolved over many years. In the early years, the focus was mainly on how to deal with the issue of increasingly scarce resources and on how to reduce the design impact on the natural environment. It is now recognized that "sustainable" or "green" approaches should take into account the so-called triple bottom line of economic viability, social responsibility and environmental impact. In other words: the sustainable solutions need to be socially equitable, economically viable and environmentally sound.

IJDST promotes the advancement of information and communication technology and effective application of advanced technologies for all design disciplines related to the built environment including but not limited to architecture, building design, civil engineering, urban planning and industrial design. Based on these objectives the journal challenges design researchers and design professionals from all over the world to submit papers on how the application of advanced technologies (theories, methods, experiments and techniques) can address the long-term ambitions of the design disciplines in order to enhance its competitive qualities and to provide solutions for the increasing demand from society for more sustainable design products. In addition, IJDST challenges authors to submit research papers on the subject of green design. In this context "green design" is regarded as the application of sustainability in design by means of the advanced technologies (theories, methods, experiments and techniques), which focuses on the research, education and practice of design which is capable of using resources efficiently and effectively. The main objective of this approach is to develop new products and services for corporations and their clients in order to reduce their energy consumption.

The main goal of the International Journal of Design Sciences and Technology (IJDST) is to disseminate design knowledge. The design of new products drives to solve problems that their solutions are still partial and their tools and methods are rudimentary. Design is applied in extremely various fields and implies numerous agents during the entire process of elaboration and realisation. The International Journal of Design Sciences and Technology is a multidisciplinary forum dealing with all facets and fields of design. It endeavours to provide a framework with which to support debates on different social, economic, political, historical, pedagogical, philosophical, scientific and technological issues surrounding design and their implications for both professional and educational design environments. The focus is on both general as well as specific design issues, at the level of design ideas, experiments and applications. Besides examining the concepts and the questions raised by academic and professional communities, IJDST also addresses the concerns and approaches of different academic, industrial and professional design disciplines. IJDST seeks to follow the growth of the universe of design theories, methods and techniques in order to observe, to interpret and to contribute to design's dynamic and expanding sciences and technology. IJDST will examine design in its broadest context. Papers are expected to clearly address design research, applications and methods. Conclusions need to be sufficiently supported by both evidence from existing research (reference to existing design research knowledge) as well as strong case-studies from any design discipline. A paper must contain at least one chapter on research questions, methodology of research and methods of analysis (the minimum length is 1500 words). The concluding chapter (the minimum length is 1000 words) will summarise the paper and its results. The concluding chapter also examines and discuss applications, advantage, shortcomings and implications of the investigation for both professional and educational design communities as well as for the people and the society. Also authors are also encouraged to include in this chapter a discussion of the possible future research that is required or is possible in order to enhance the research findings.

The papers considered for IJDST cover a wide range of research areas including but not limited to the following topics: Design research, design science, design thinking, design knowledge, design history, design taxonomy, design technology, design praxeology, design modelling, design metrology, design axiology, design philosophy, design epistemology, design pedagogy, design management, design policy, design politics, design sociology, design economics, design aesthetics, design semantics, design decision-making, design decisions, design evaluation, design sustainability, design logic, design ontology, design logistics, design syntaxis, design ethics, design objective, design responsibility, design environment, design awareness, design informatics, design organization, design communication, design intelligence, design evaluation, design education, design theories, design techniques, design methods, design operations, design processes, design products, design users, design participation, design innovation, design inspired by nature, design case studies, design experiments, etc.

International Journal of Design Sciences and Technology is devoted to further exploration of all themes and issues that are directly or indirectly relevant to the exploration, introduction, discussion of design sciences and technology, cross referencing domains and any other themes emerging in the future.

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