Investigating Design Representation
Implications for an Understanding of Design Practice

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Abstract: Industrial design practice is characterised by the use of design representations as embodiments of design intentions. From the ubiquitous sketch through to high fidelity prototypes, the designer employs a variety of representations to externalise and develop solutions to often ill-defined design problems. Reflecting their importance to design activity, efforts have been made to identify, define and classify the attributes of these various representations. This study synthesises these previous efforts in a qualitative analysis of 50 industrial design case-studies identified through literature review. Images of design representations and their associated captions were segmented using thematic criterion, resulting in 419 coded design representations. Results show that the attributes of design representations often defy clear identification and description. New approaches aimed at the identification, description and classification of design representation employed during concept and developmental design are required. These methods must be sensitive to the often ambiguous, richly idiosyncratic and unstructured nature of conceptual design representation. The paper concludes by arguing for approaches to analysis, description and classification that focus upon purpose of use as a strategy to define and explain design representation and the critical role it plays in designerly ways of thinking and action.

Key words: Design representation, design practice, taxonomic classification

1. Introduction

From the concept sketch to pre-production prototypes design representations are utilized as essential tools in support of design activity (Visser 2006, Goldschmidt & Porter 2004). Designers use these embodiments of design intent for various purposes, from thinking, reasoning and the clarification of thoughts and ideas to the specification of design intent to clients and other stakeholders (Visser 2006, Goldschmitch & Smolkov 2006, Pei et al., 2011, Cross, 2000). These design representations support both the designer's own reflections upon their own developing ideas (Schon 1991) and communication and interaction among stakeholders (Cross 1999, Alisantoso & Khoo 2006). Considering their various and critical role in support of design practice, studying design representation provides opportunities to develop understanding of the nature of design activity and the kinds of knowing and thinking it entails (Cross 2007).

In an early work related to the use of design representation in practice Tovey et al. (1989) explored the characteristics of CAD representations, proposing directions for CAD system development by comparing the use of CAD and traditional drawings in automotive design. Johansson et al. (2001) investigated the use of design representations as they relate to design activity through a field study of industrial companies. Results suggested design firms use a variety of representations for different purposes and that the attributes of conventional (sketching and hand drawing) and digital (CAD models) representation methods influence their use in practice.

Other studies have dealt with the relationship between communication and design representation more specifically. Alisantoso & Khoo (2006) suggested a purpose-behavior-structure representation scheme in order to improve the communication of non-functional and functional design purposes among various stakeholders in product development. Pei et al. (2011) developed a taxonomic classification of design representations to help communication and collaboration between industrial and engineering designers during new product development. Research by Engelbrektsson and Soderman (2004) focused upon communication of design intent to potential consumers in an effort to identify customer requirements. The investigation explored the effect of various product representations as communication tools.

Often, the investigation of design representation is seen as a valuable means to explore design practice and the particular kinds of knowing and thought it involves (Visser 2006, Cross, 2007). For example, Cross (1999) presents research to develop understanding of the nature of design problems through an investigation which analysed the role of sketch. Do et al. (2000) attempted to interpret the designers' thinking through a study of the kinds of drawings produced in support of studio practice. Through developing notation systems which focus on transformation from one drawing to another, the study considered the role of drawings and the relationship it has to outstanding design. In his seminal text Geol (1996) explores the designer's use of sketching in a comparative study in order to challenge a computational theory of the mind. His work suggested important insights into the role sketching plays during a more divergent, conceptual design activity due to its ambiguous nature and density as a form of design representation.

Much existing work related to investigations of and into design representation has focused upon understanding their use and significance through the analysis of individual tools. However, in contemporary practice, designers employ a wide variety of design representations, deployed at different phases in design development, for different purposes in support of the various requirements of practice (Pei 2009, Stolterman et al., 2008). In order to develop an understanding of the significant role design representation plays in support of design activity, it is important to develop descriptions of the various characteristics of design representations. These descriptors may then form the basis of a classifications system. That is, the best approaches to identify and develop an understanding of a complicated phenomenon, such as the use of design representation, is to first analyse its constitute elements through classification (Simon, 1996).

2. Taxonomic Classification of Design Representations

Although not specifically aimed at understanding the significance and use of design representation, the taxonomy developed by Pei et al (2011) describe design representations in terms of the various roles they play as means of communication between industrial and engineering designers. Pei et al's. (2011) systematic classification provides an indication of the nature of design activity as various design representations are employed, from the ambiguity of a thinking sketch to the fidelity of a pre-production prototype (ibid). This is also indicative of the kinds of information exchanged during each stage in the design process, form divergent, conceptual exploration to convergent specification during detail design. Similar to Pei et al (2011), Asanuma et al. (2007) description and classification of design modelling methods through clustering has suggested a set of guidelines to support practitioners in their choice of appropriate models. In research by Schenk (2007) an original taxonomy of design drawings based on their use is presented. The study proposes the use of the taxonomy which characterises, classifies and analyses drawings will help less experienced designers understanding the nature of design drawings. In contrast, Gershenson and Stauffer (1999) developed a taxonomy to deal with the design requirements for product design in a more effective way. Their system of classification aims to contribute to the product design process in terms of gathering and managing design requirements which are then deployed in defining product specifications.

Existing research employing taxonomy as a means to identify, describe and classify design representation indicates the advantages of classification. Through classification, hierarchy and relationships among taxons, dimensions or categories may be identified in order to develop a richer, more holistic understanding of the whole system of representation. The study presented here builds upon this existing work through an analysis of design representations. This analysis is then used to consider the benefits and any limitations of existing classification systems and how they may be improved.

3 Research Aim

The research contributes to an understanding of the role and significance of design representation as it supports designerly thought and action. Specifically, the study aims to contribute to existing attempts to classify design representations as a means to consider their role and significance for design practice. With these aims in mind the study addresses the following research questions: 1. How effective are methods of taxonomic classification in the identification, description and categorisation of design representation? What can an analysis of the effectiveness of taxonomic classification tell us about the nature of design representation and the kinds of thinking and action it supports? The reflection upon and communication of design intentions, through design representation, appears to be critical to the kinds of thinking, knowing and acting engaged with during design practice (Visser 2006, Goldsmitch & Porter 2004, Buxton, 2007 Cross, 2007). In addressing the research questions above the authors sort to contribute to a growing body of work which seeks to understand designerly ways of thinking, knowing and acting through the investigation of design representations, their significance, role and use.

4 Research Methods

The study employed qualitative content analysis to identify, classify and describe design representations used in support of design practice. Through literature review, case studies of design practice were identified (Bjornlund et al., 2001; Cullen and Haller, 2004). These cases, presenting and describing the use of design representations, constituted the study's units of analysis. In total the study analysed 50 case studies to identify and describe the types of design representations used and to then classify them through the application of a part theory, part data-driven coding frame. Images of design representations within the 50 cases were segmented using thematic criterion into units of coding. That is, images of design representations and their associated captions were segmented into units of coding according to the different attributes of the representations presented in the case-studies. In order to reduce the likelihood of subjectivity in the segmentation of the design representations, a sample of representation (10 case-studies) were segmented into units of coding by 2 coders individually. Any differences in segmentation were then discussed. This process resulted in 419 instances of coding across the 50 case-studies.

In order to describe and categories the design representations identified in the case-studies, a part concept, part data-driven coding fame was constructed, developed and revised during the coding of the segmented design representations. Taking as a starting point the categories used in an existing taxonomy of design representations (Pie et al., 2011), the 4 main categories or dimensions of the coding frame were defined. These 4 dimensions, relating to the 4 phases of the design process, were given the titles Concept, Development, Embodiment and Detail design (Baxter 1995, Ulrich & Eppinger 2012). Within each, a number of subcategories were added.

The coding frame was then piloted with a sample of the units of analysis (10 of the 50 design case studies). The segmented representations (units of coding) within each of the 10 cases were coded by 2 separate researchers and the results subsequently compared in order to improve inter-rater reliability. The pilot highlighted the inadequacies of the coding frame to describe all the segmented representations within the cases. Comparing the coding result, the coding frame was refined. Considering the causes of disagreement, the names and definitions of subcategories within the frame were modified, branched, merged, removed or moved to other dimensions of the coding frame.

Using the revised coding frame a second pilot coding was conducted across the 10 case studies. For this iteration, a code for each subcategory was added to indicate dimension of coding (C: Concept, Dv: Development, E: Embodiment, Dt: Detail), representation type (S: sketch, D: drawing, M: model & P: prototype) and listed order (1, 2, 3 and so on). For example, Idea sketch which is the first subcategory on the concept design dimension of the frame was named C.S1. The segmented representations were re-coded using the refined coding frame by 2 coders separately and the results again compared. After a third and final pilot coding across the 10 case-studies, which resulted in some minor revisions to the coding frame, the final coding frame presented in Figure 1 was obtained.

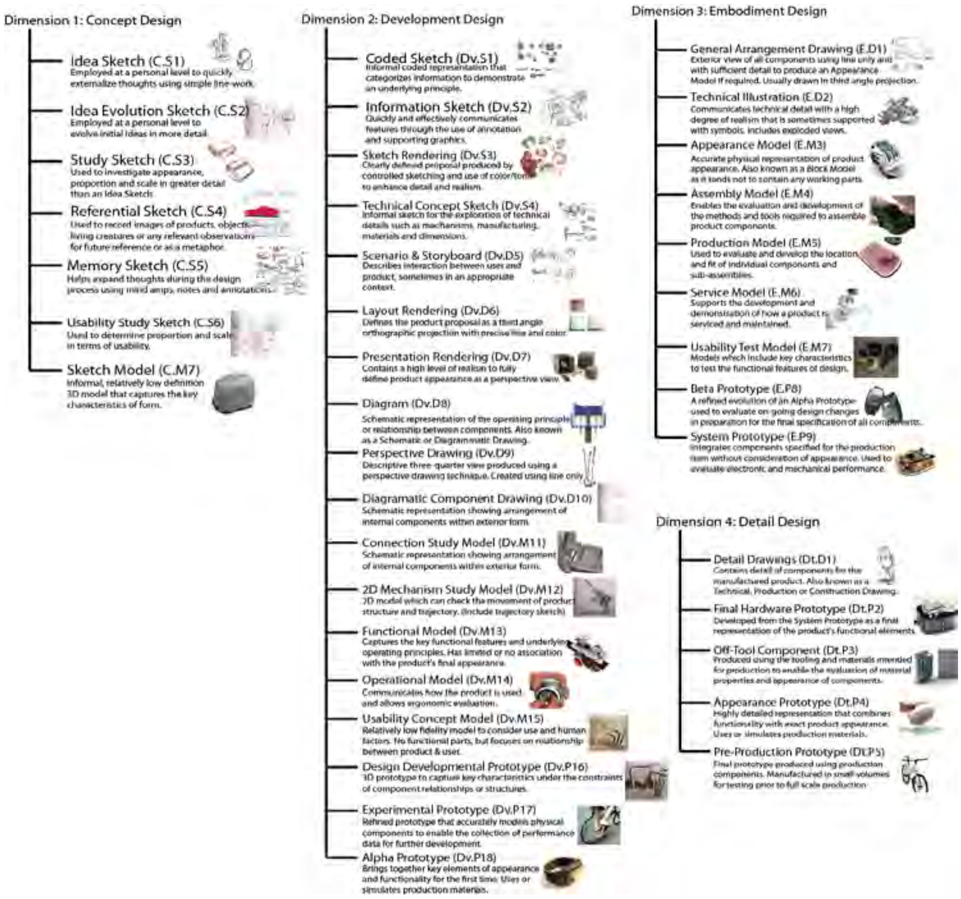

Figure .1 Final Coding Frame

The revised coding frame was then used in a qualitative analysis of 50 cases of design practice. The segmented design representation within the 50 case studies, were coded 419 times across the 4 dimensions of the coding frame.

5. Results

The study's research aim and questions informed both the methods of analysis and the presentation of findings. This section presents results in order to assess the effectiveness of taxonomic classification as a means to describe and classify design representations (research question 1).

A subsequent discussion section then considers what implications findings have for an understanding of design representations and the kinds of thinking and action they support (research question 2)

5.1 Revisions to the Coding Frame

Comparing the first and the final version of the coding frame (Figure 1 above), the number of subcategories increased across three of the 4 dimensions of the frame. Changes in the number of sub-categories for each dimension are compared in Table 1.

Table 1. Comparison of changes to coding frame across 4 dimensions

Dimension of Coding Frame	1: Concept Design	2: Development Design	3: Embodiment Design	4: Detail Design
Sub-categories, 1st version of Frame	**4**	**15**	**8**	**5**
Sub-categories , Final version of Frame	**7**	**18**	**9**	**5**
Revised, Added and/or removed sub-categories	**3**	**7**	**1**	**0**

Along the concept dimension of the coding frame a total of 3 categories were revised, added or removed. This compared to a total 7 in the case of Development Design, 1 for Embodiment Design and 0 for the Detail Design dimension. Figure 2 illustrates the revisions to the coding frame along the Concept Design dimension. The 3 Revised sub-categories are indicated within red, rectangular boxes:

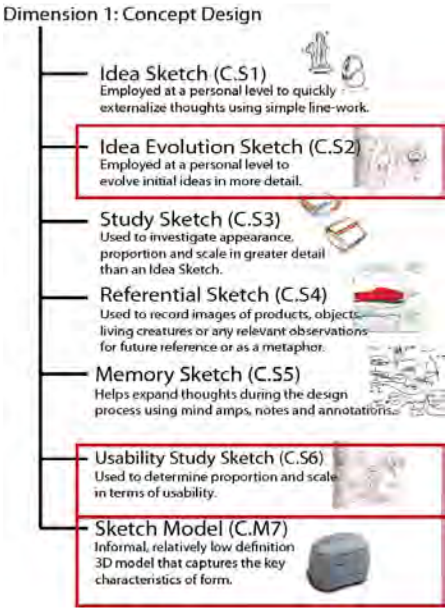

Figure .2 Revisions to coding frame across Concept Design dimension

The application of the 1st version of the coding frame in the analysis of the segmented design representations indicated the presence of some units of coding that defied description. That is, none of the subcategories within the frame adequately described a number of the design representations. As a result 2 additional subcategories were added: Idea Evolution Sketch (C.S2) and Usability Study Sketch (C.S6), Figure 2. The subcategory Idea Evolution sketch (C.S2) was generated in response to representations indicating the designers' exploration of ideas, but with a focus upon evolving initial ideas in more detail. Figure 3 illustrates an example design representation coded as an 'Idea Evolution Sketch'.

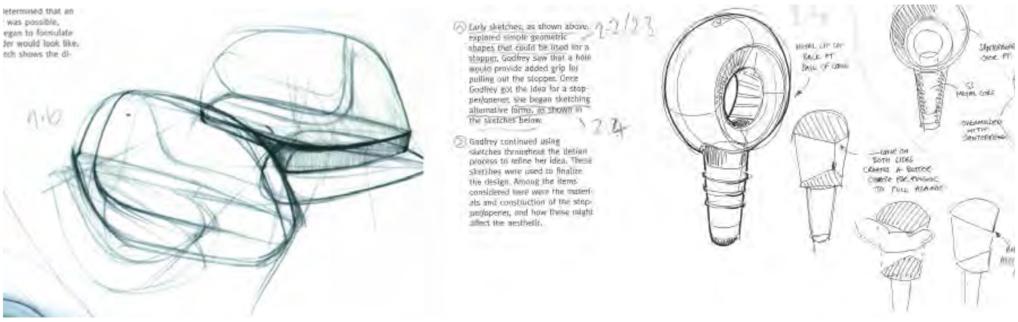

Figure .3 Example Idea Evolution Sketch representation (C.S2) & Usability Study Sketch representation (C.S6)

The 2nd added sub-category, 'Usability Study Sketch', was generated in response to representations identified within the case studies that suggested the designer's concern for usability during conceptual design (Figure 3). The Original coding frame consisted of sub-categories along the concept dimension that described various types of sketch representation only. However, an analysis of the design representations within the case studies suggested the use of low-fidelity sketch models during conceptual design. As such, the subcategory 'Sketch Model' was moved from dimension 2, Development Design to dimension 1 Concept Design. Figure 4 illustrates the subcategories included in the final version of the coding frame under dimension 2, Development Design.

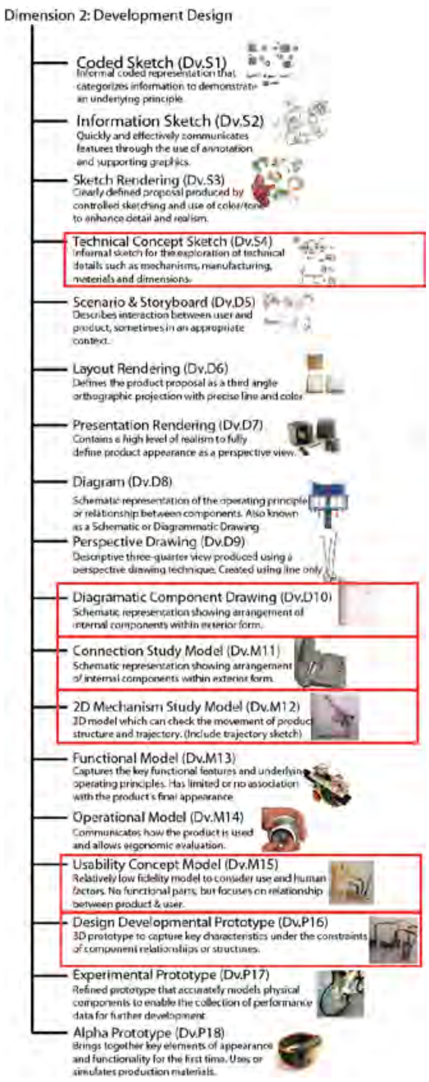

Figure .4 Revisions to coding frame across Development Design dimension

A total of 4 new subcategories were added to the dimension as a result of the application of the 1st version of the coding frame in the analysis of design representations: Diagrammatic Component Drawing (Dv.D10), Connection Study Model (Dv.M11), 2D Mechanism Study Model (Dv.M12) and Usability Concept Model (Dv.M15). As well as these added subcategories, Design Development Prototype (Dv.P16) was revised from Design Development Model and the sub-category Sketch Model was moved to the Concept Design dimension. Finally the original category 'Prescriptive Sketch' was revised to 'Technical Concept Sketch', Dv.S4.

Through an analysis of the segmented design representations, units of coding were identified that illustrated the designer's attempts to systematically illustrate the arrangement of internal components within the exterior form. These were often produced as sketches or drawings. In response Diagrammatic Component Drawing (Dv.D10) was added to the coding frame (Figure 5 illustrates an example coding).

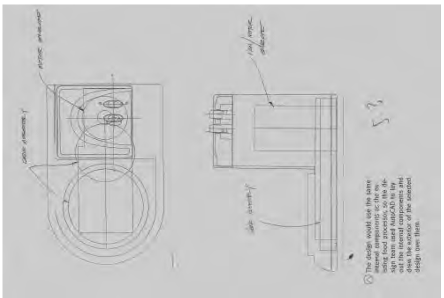

Figure .5 Example of Diagrammatic Component Drawing (Dv.D10

The added category, 'Connection Study Model' (Dv.M11, Figure 8) illustrated the use of simple mock-ups in the exploration of relationships between components. These models often appeared to include moving parts with a focus on relationships between components (Figure 6).

Figure.6 Example Connection Study Model (Dv.M11) & Example 2D Mechanism Study Model (Dv.M12)

The subcategory '2D Mechanism Study Model' (Dv.M12) was created in response to the identification of representations as 2D models used to check intended structure and trajectory (Figure 8). Finally the subcategory 'Usability Concept Model' (Dv.M15) was added to code relatively low fidelity models identified within the analysis of representations that appeared to focus upon usability and human factors but with no moving parts (Figure 7).

Figure .7 example of Usability Concept Model (Dv.M15)

The revised category Design Development Prototype (Dv.P16) identified and coded 3D prototypes used to capture key characteristics under the constraint of component relationships and structures. The revised sub-category Technical Concept Sketch (Dv.S4) was used in the coding of representations identified as informal sketches used in the exploration of technical details such as mechanism and processes of manufacture. Figure 8 illustrates the final version of the coding frame's 3rd dimension, Embodiment Design.

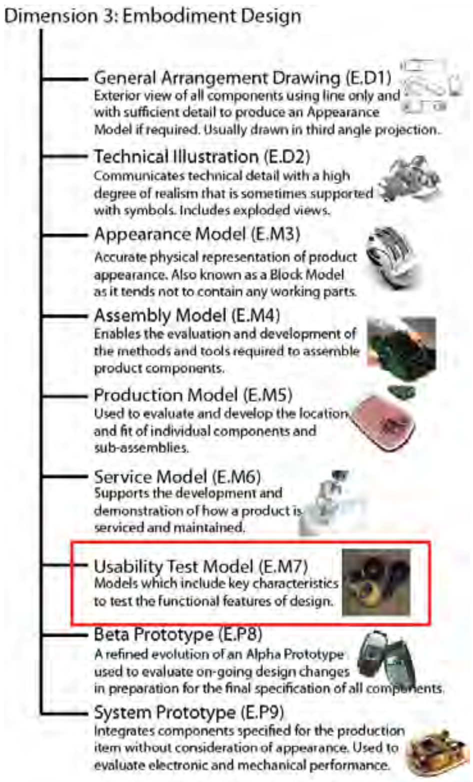

Figure .8 Revisions to coding frame across Embodiment Design dimension

Only 1 revision was made to the dimension Embodiment Design in the final version of the coding frame. The subcategory Usability Test Model (E.M6, Figure 9) was added. This new category was used in the coding of design representations as models which appeared to focus on the function features of design. Figure 12 provides examples of representations coded as Usability Test Models.

Figure .9 Example of Usability Test Model (E.M6)

Finally, the 4th dimension of the final coding frame was not revised between the 1st and final versions. Figure 10 illustrates dimension 4 of the coding frame.

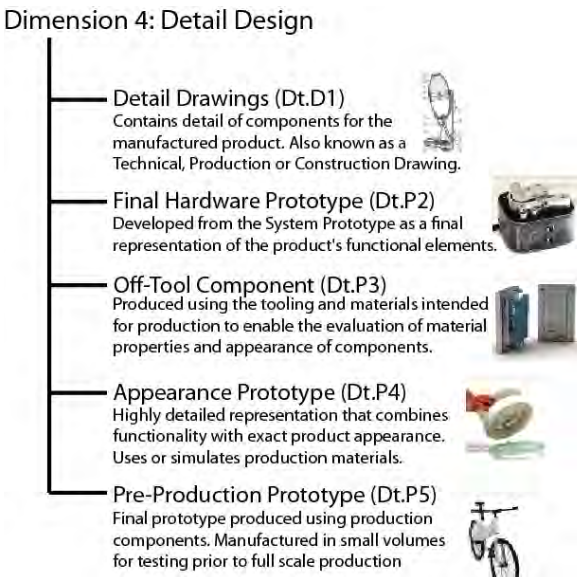

Figure .10 Coding frame across Detail Design dimension

The application of the first coding frame in the qualitative content analysis of segmented design representations indicated inadequacies in its ability to code all the segmented units of coding. This resulted in a number of data-driven revisions to the coding frame until saturation was achieved.

Where revisions were made it was in response to the frame's inability to code representations. That is, the subcategories within the 4 dimensions did not describe the representations identified within the case studies. A majority of these revisions were made to dimensions 1 and 2 (Concept and Development Design), totaling 10 revisions. In contrast only 1 revision was made to the Embodiment and Detail Design dimensions (see Table 1 above). This indicates while existing taxonomic classification through the analysis of design representations is effective in describing and classifying those representations associated with a more convergent and specific phase in design development (embodiment and detail design), it's use in the description and classification of lower fidelity, more ambiguous representations is problematic. This suggests that taxonomic classification has potential as a means to describe the significance and use of those representations employed during embodiment and detail design activity. That is, their identification, description and classification can be identified un-problematical. In contrast, those representations associated with concept and development design were more resistant to identification and description within a structured taxomic classification system.

5.2 Inter-Coder Agreement

Further evidence to indicate the limitations of taxonomy as a means to identify and describe conceptual design representations was identified when levels of inter-coder agreement between coders was compared across the dimensions of the coding frame. Table 2 shows the number of times disagreement between coders was detected across each of the frame's 4 dimensions when coding a sample of 10 of the 50 case-studies to check consistency of coding. Design representations coded along the Concept Design dimension indicated most disagreement (53%) followed by Development design 46%, Embodiment Design (42%) and Detail Design (17%).

Table 2 Agreement between coders across dimensions of coding frame

	Concept Design	Design Development	Embodiment Design	Detail Design
No. of disagreement	22	23	8	2
Disagreement rate (%)	53	46	42	17

The disagreement rate between coders indicated the amount of subjectivity required in coding design representations across the 4 dimensions. In contrast with the first 3 dimensions of the frame, those representations coded along the Detail Design dimension suffered far less from inconsistency in coding (17%).

5.3 Double Coding of Design Representations

In the qualitative analysis of the segmented design representations, the various representations were coded, if appropriate, across more than 1 dimension of the coding frame. That is, a unit of coding (segmented representation) was coded by more than 1 subcategory if a representation was equally well described by more than one subcategory. However, in order to retain the integrity and validity of the coding frame, representations were not coded as more than 1 subcategory within the same dimension. Figure 11 illustrates the 4 dimensions of the coding frame (Concept, Development, Embodiment and Detail Design), absolute frequencies of coding for each dimension (black) and frequency of double coding within each dimension (red).

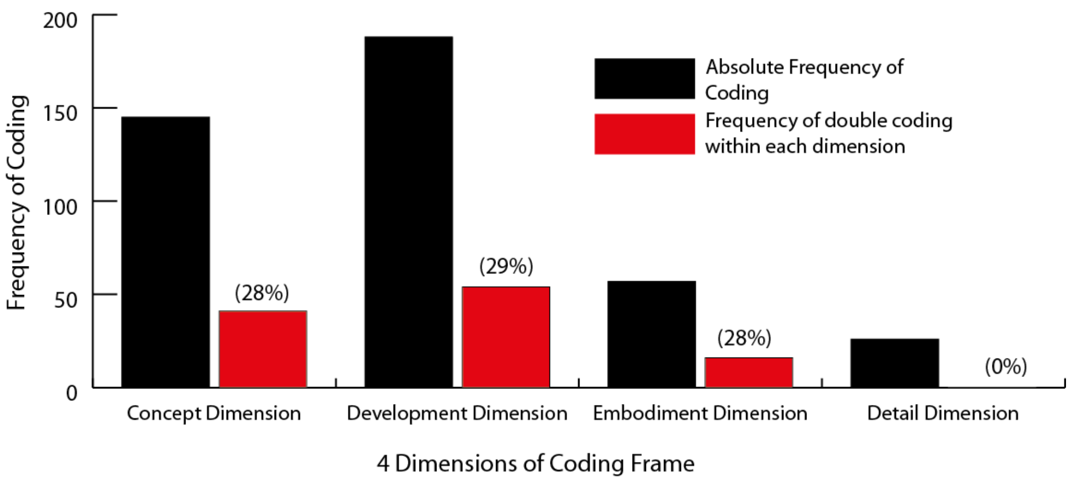

Figure .11 Absolute frequencies of coding across dimensions and frequency of double coding

As a percentage of absolute frequency of coding, 3 of the 4 dimensions within the frame included an almost identical frequency of double coding (Concept 28%, Development 29%, Embodiment 28%). There were no instances of double coding within the Detail Design dimension of the frame. Further analysis of the spread of double coding across these three dimensions indicated instances of double coding were most often found between the Concept and Development design dimensions (40 instances), followed by the Development and Embodiment dimensions (15). 1 instance of double coding was also identified between Concept and Embodiment Design (Figure 12).

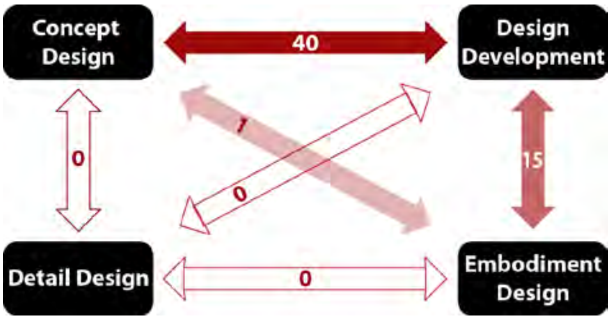

Figure .12 Instances of double coding between dimensions

Figure 13 presents the 5 subcategories most often used in the double coding of representations, absolute frequencies of coding (black) and frequencies of double coding (red).

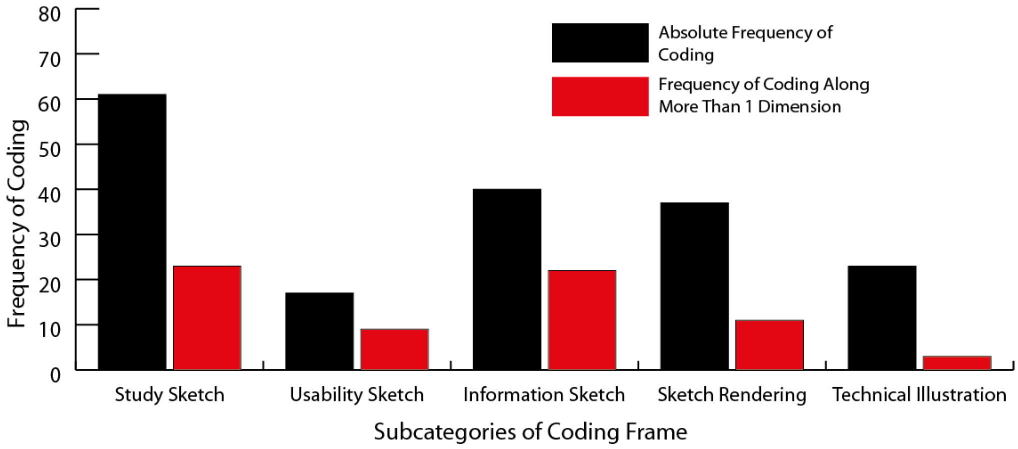

Figure .13 Subcategories most often used in the double coding of representations.

Those design representations often coded across more than 1 dimension were design sketches of various kinds and those representations coded as ‘Technical Illustration’ (Figure 15). This suggests that those representations often associated with conceptual design, particularly the hand sketch, were also those most lightly to be coded by more than 1 subcategory across 2 dimensions. This was again indicative of the coding frame’s limitations in identifying and describing the individual sketches and representations often made in support of conceptual and developmental design practice. That is, those representations often associated with a divergent, conceptual design activity can defy clear classification and description though a systematic taxonomic classification system.

6. Discussion

Between the first and final iteration of the coding frame more revisions were made to the Concept and Development dimensions than embodiment and detail design (Table 1). This indicated a limitation in the original version of the frame to account for all the segmented representations analysed across the 50 case-studies. Moreover, even after the revision of the coding frame, inter-coder disagreement was high among the first 3 dimensions of the coding frame (Table 2). However, disagreement was far lower for those representations coded using the frame’s 4th dimension, Detail Design. This indicated the limitations of the coding frame in its ability to effectively identify and clearly describe design representations with the exception of those associated with detail design practice. Instances of double coding (the coding of representations across more than one dimension of the coding frame) was most prevalent between the Concept dimension and the Development dimension, although 15 instances of double coding were also identified between the Development and Embodiment dimensions. In contrast no instances of double coding accrued between the Detail Design dimension and any other. Finally, sketching was identified as a type of design representation most susceptible to double coding across the coding frame (Figure 16).

These findings indicate the limitations of systematic, taxonomic classification in its ability to identify and describe those representations often associated with a more divergent or conceptual phase in design development. It appears that these representations often defy identification and classification. Despite an increase in the subcategories of dimension 1 (Concept Design) and 2 (Development Design) instances of both disagreement between coders and double coding across these dimensions were high. It appears the rich and varied nature of those representations often associated with conceptual and developmental design activity mean their description and classification through systematic methods has some limitations. Ambiguity in design representation as well as variety, style and idiosyncratic attributes mean the clear interpretation of these representations appears difficult to achieve. This would agree with existing work related to the character of conceptual representations and their influence on design thought and actions (Goel, 1996, Visser 2006).

It may be that the mixture of purposes and information present in those representations associated with a front end of design development, particularly sketches, mean they remain resistant to clear interpretation and classification. In contrast, the ability to identify those representations associated with detail design may be related to an ability to clearly perceive the purpose of and motivations for design representation. That is, designers utilize design representations, mostly drawings and prototypes, to specify their design ideas and determine design factors through considering feasibility and requirements for product manufacturing. Reflecting these requirements, design representations at a later stage in practice are produced in more structured ways with a clearer purpose in mind. This characteristic of design representation not only supports better communication among different design stakeholders, but also makes categorisation far less challenging.

It appears, although the purpose of design activity evolves and develops, from divergence to convergence and in response design representation moves from lower to higher fidelity, identifying these movements as discreetly different types of representation may not best reflect the dynamic, often iterative practice of design. These findings support the view of design activity at a conceptual or highly developmental stage in practice as characterised by a rich, unconstrained and ill-disciplined way of thinking and acting. This kind of thought and action may resist more structured attempts to identify and describe the representations that support it. In contrast, as the kinds of thinking and representation required to explore and define product attributes is mostly complete prior to detail design, representations are used at a later stage in design development with a clear aim or purpose in mind; to confirm and specify manufacturing issues prior to production for example.

In order to begin to identify and describe the kinds of thoughts and actions at work in the representation of design intentions during a more divergent and ill-structured conceptual design activity, it may be advantageous to analysis not the representations themselves but the kinds of motivations for their construction. That is to say, an analysis of design representation with a clear focus upon purpose(s) may prove more effective in its ability to identify and dissect the ill-defined nature of the conceptual design representation. In doing this we will be better placed to describe the nature of design representation during conceptual and developmental design and the kinds of designerly ways of thinking and acting it requires and supports.

7. Conclusions

This study employed qualitative content analysis in order to assess the effectiveness of taxonomic classification as a method to identify, describe and classify the various design representations used in support of design practice. Findings support the use of systematic classification for the description of design representations used at a more convergent and constrained stage in the design development process. However, results also indicate the limitations of classification in its ability to define and describe those representations often associated with a more divergent and explorative design activity; conceptual and developmental design representation.

Results support previous work which has described the ill-defined and ill-structured nature of design representation made at an early stage of design development. Findings suggest the aim or purpose of design representation during conceptual and developmental design may be more subtle and multi-facetted in nature. In order to effectively analyse these lower-fidelity more ambiguous representations we propose analysis methods sensitive to the underlying motivations for representations are required. In this regard future work to analysis the various motivations for and construction of design representations at a conceptual stage in practice may provide opportunities to more precisely identify describe and explain their role and use. Future studies may attempt, for example, to classify representations with a greater focus upon purpose or purposes of use: design representations as they are used to persuade, to describe, explain, explore, specify, inform, define and verify for example. Through existing work, this study's findings, and future investigations aimed at developing an understanding of design representation, its role and use in practice, we will in turn contribute to knowledge and understanding of the kinds of designerly ways of thought and action embodied in the representation of design intentions.

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