Multi-scale analysis of the engineering design process: A protocol study of design in practice

Abstract

This paper contributes to the on-going research aimed at improving our understanding of design activity and design practice. Specifically the paper presents a multi-scale analysis of the activity of three engineering designers over a period of one month. Design activity is widely researched at various scales e.g. process or individual cognition but rarely across scales. This paper represents the first work that explicitly investigates activity across the different scales of macro, meso and micro. In addition to discussing the underlying relationships between the scales of design activity, the paper elucidates key implications for design research and practice by articulating a holistic view of design as a complex fabric of interwoven processes. This discussion also highlights important areas of future research.

Keywords: case study, design activity, design practice, protocol analysis,

Understanding, and describing the design process has been a focus of design research since its inception (Cross, 2007; Pahl & Beitz, 1996). Being able to describe the activities and cycles associated with a successful design process, and subsequent design outcome, form some of the fundamental ambitions of the field (Finger & Dixon, 1989a, 1989b; Horvath, 2004). The scope of this ambition is illustrated by two perspectives widely represented in current design research literature. First, fine grain approaches are used to understand the details of micro-scale cycles or processes linked to design performance e.g. design cognition for shared mental models (Dong, Kleinsmann, & Deken, 2013). Second, coarse grain approaches are used to map wider, macro-scale, processes or overall features of design activity e.g. stage based descriptions of design (Cooper, Edgett, & Kleinschmidt, 2002; French, 1998). Here each type of approach is facilitated by, and results in, explanative frameworks or models appropriate to that type of research e.g. micro-scale team interaction models (Dorst & Cross, 2001; Gero & Kannengiesser, 2004; Visser, 2010), or macro-scale associations between total time spent on a specific activity and overall performance (M. A. Robinson, 2010; Wasiak, Hicks, Newnes, Dong, & Burrow, 2010). Despite the strengths of these individual perspectives, they by necessity adopt empirical methods applicable to the different scales (Lethbridge, Sim, & Singer, 2005). Consequentially, this leads to a fundamental issue when considering, and trying to bring together, these different aspects of the design research domain (McMahon, 2012): The difficulty in exploring and characterising if, and how, micro-scale and macro-scale features are related, and what exists in the middle ground.

Although comparisons exist within a scale, the Authors have been unable to identify extant studies that span the scales. For example, consider the recent work of Cash et al. (2013), where situations were compared in practice and in the lab. Although this focused on bringing together research perspectives, it was limited to micro-scale features and was fundamentally informed by the designer level perspective. Also consider the debates surrounding differences between practitioners and students (Ahmed, Wallace, & Blessing, 2003; Kavakli & Gero, 2002; Seitamaa-Hakkarainen & Hakkarainen, 2001). Here there are many comparisons at each scale but few studies bridging experimental and longitudinal data in order to more fully understand the implications of short-term differentiation. The lack of consideration of multi-scale relationships is further illustrated by Robinson's (2010) work on information behaviours. Although this is notable for its method's longitudinal quality, it is also limited by the difficulty in linking to the micro-scale structures of minute-by-minute information seeking. This fundamentally limits the understanding that can be generated from comparisons between studies. Hence it can be argued that, as with any technical system, the ability to describe behaviours and properties of the system across multiple scales is essential for generating deep scientific understanding. Further, this is true also for social-technical systems, such as, the activity of design, and thus the exploration and consideration of multiple scales is an important element in furthering the understanding of design as a whole.

Ultimately these points can be distilled into the driving question for this work: *how are the various scales of design activity related i.e. how do micro-scale structures link to macro, and possibly meso-scale structures?*

In order to answer this question, the work develops a multi-scale analysis using an observation study of practice. Specifically, a fine grain protocol analysis is used to describe a longer period of design activity in order to facilitate analysis at three scales (discussed later) using a single dataset. In order to set the stage for such a comparison the next section presents an overview of research on design activity at the various scales of analysis. The study method is then described (Section 2) and in depth results presented and analysed (Section 3). Subsequently, implications for both research and design practice are elucidated (Section 4) before, conclusions are drawn and a number of key areas for further research proposed (Section 5).

1 Background

In order to empirically explore how different scales of design activity research can be linked, two areas need first to be considered: I) How can the various scales be brought together in a coherent theoretical framework? And II) How have the different scales been treated to date? These are discussed in the following subsections.

1.1 Activity Theory as a Unifying Lens

In order to explore the first area we look to Activity Theory as a possible framework for describing design activity across scales (Bedny & Harris, 2005; Jonassen & Rohrer-Murphy, 1999; Leont'ev, 1978). The intention here is not to fully explore Activity Theory but merely explain its role in providing a lens for unifying understanding of different scale processes in a single framework.

Despite some partial uptake in design (Moser, Ziegler, Blessing, & Braukhane, 2012; von Saucken, Schroer, Kain, & Lindemann, 2012) no definitive works exist within the field. As such, Bedny and Harris (2005) are used as the basis of the descriptions articulated here. With respect to the multi-scale focus of this work, Activity Theory articulates a structured means for describing complex, multifaceted, and multilevel activity (Bedny & Harris, 2005). Here activity is characterised hierarchically in the following parallel framework (Bedny & Harris, 2005; Bedny & Karwowski, 2004; Jonassen & Rohrer-Murphy, 1999):

Activity ←→ Action ←→ Operation

Motivation ←→ Goal ←→ Conditions

This framework unites activity associated with high-level motivations, e.g. dismantling a machine, with conscious, and unconscious actions, and operations. Here, this framework gives two key benefits.

First, it allows for multiple parallel and series elements to be considered in a cohesive manner. Here, activities or groups of activities can be described in parallel, while tasks, actions, and operations are treated in series. For example, at the activity level a designer might work on both the development of a concept, and gathering information for a stage-gate report. However, at the task level they can either sketch a concept or find technical documentation. Further, at the action level, people are only able to complete one action at a time e.g. moving a pencil over the concept to draw a line. This combined framework provides an important lens for the unified assessment of design work, particularly where there is sparse theory. This links to the complex nature of design activity, with multiple simultaneous processes at various scales (Bucciarelli, 1988; Cross & Cross, 1995; Dorst & Cross, 2001; Gero, 1990).

Second, it is possible to conceptually expand the *activity – action – operation* framework in order to describe groups of activities, in a similar manner to how actions can be grouped at the lower levels (Bedny & Harris, 2005). In the context of design, this allows for a more cohesive description of design work to be proposed i.e. linking cognitive level operations to large-scale groups of activities and ultimate design process stages. This is similar in conception to the idea that the design process itself is one part of the wider innovation process (Cooper, 1988). As such, this gives an ideal conceptual frame for linking macro and micro level features of design work.

Based on Activity Theory a triple-scale research framework is articulated in Figure 1 and is proposed in order to frame the discussion of design activity, the multi-scale analysis and the results. A triple-scale of macro, meso, and micro-scales is proposed based on exploration of the existing design literature.

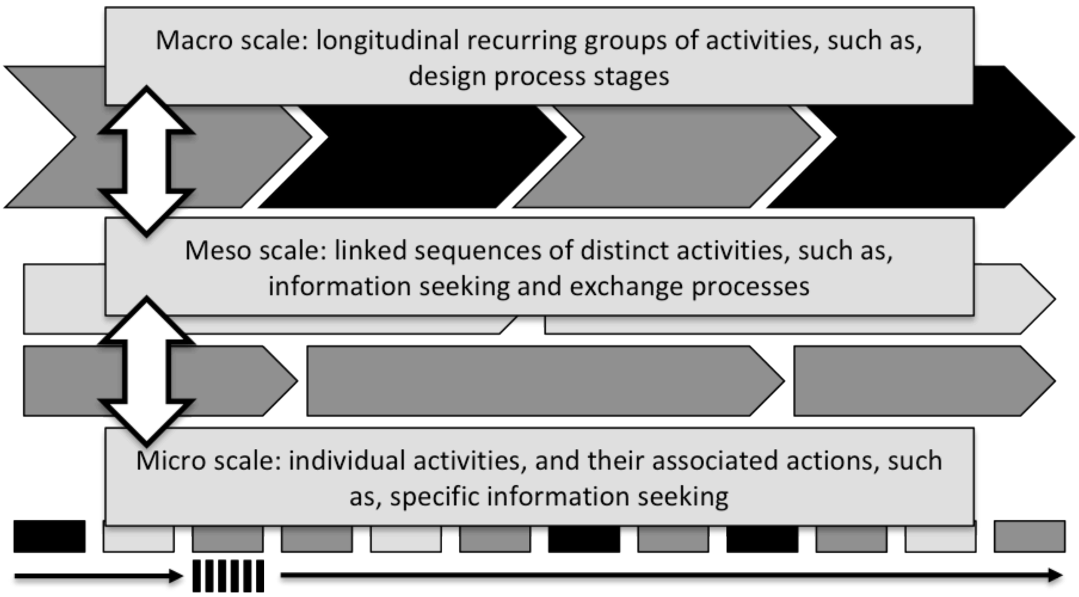


Figure 1: Research framework linking macro, meso, and micro-scale processes based on Activity Theory

1.2 Observation of Design Activity

In reference to the proposed multi-scale research framework of design activity (Figure 1), it is possible to identify key research at each scale, but critically, little across scales. In many ways the bifurcation of design research perspectives can be traced back to the differing stances that dominate the field. Horvath (2004) highlights human aspects on one hand (*design knowledge, human assets*), and non-human aspects on the other (*process knowledge, artefact knowledge*). In the context of design activity this leads to two perspectives: human up (cognition and behaviour) –

typically focused on the micro-scale, and process down (stages and artefact evolution) – typically focused on the macro-scale. In order to understand current thinking with respect to these perspectives this section explores each of the scales identified in Figure 1 with respect to the extant design literature.

Macro-scale

The macro-scale of design activity deals with processes occurring with a low frequency across the whole design processes. For example, the changing focus of work, coupled with regular stage gate reviews described by Ulrich and Eppinger (2003) is one such process. In general, studies of these processes build external validity by adopting longitudinal sampling approaches, which can be directly tied to specific attributes of the examined cases. Here, methods are geared towards capturing coarse grain activity over long periods of time. For example, multiple case studies (Eisenhardt & Graebner, 2007), statistical analysis of covariance between variables (Patanakul, Chen, & Lynn, 2012), or linking to theoretical models e.g. innovation processes (Pearce & Ensley, 2004). However, generalising across cases, contexts or processes can prove difficult where underlying theory is poorly integrated or where contextual variables are not fully understood. Further, the relationship between micro and macro-scale processes are often only linked via logical argument. For example, Qureshi et al. (2014) highlights a number of key features of the product lifecycle and how it evolves over time in different models. However, it is difficult to directly relate these high level process conceptions to lower level studies of detailed design activity where there are a number of competing perspectives (Cross, Christiaans, & Dorst, 1996; McDonnell & Lloyd, 2009). In particular there is little work explicitly exploring how these macro-scale processes affect smaller scale activity.

Meso-scale

Meso-scale processes consider a wide array of perspectives. Recent examples include information behaviours during the design process (M. A. Robinson, 2010), e-communication patterns over time (Wasiak et al., 2010), and the use of engineering documents (Wild, McMahon, Darlington, Liu, & Culley, 2010). Here, methods focus more on groups of activities or other process elements supported by micro-scale processes. This scale draws on mid-level theory such as organisational or group information processing (Hult, Ketchen, & Slater, 2004; Siebdrat, Hoegl, & Ernst, 2013), communication dynamics (Maier, Eckert, & Clarkson, 2005), or decision making (Schmidt, Montoya-Weiss, & Massey, 2001). For example, Robinson (2010) highlights a number of key features of information behaviour and how it changes over time. However, given the recorded data it is impossible to directly relate these to lower level studies of detailed information activities where there are a number of competing perspectives (Holscher & Strube, 2000; Keller, Sleeswijk Visser, van der Lugt, & Stappers, 2009). Thus, while acknowledging that activity at this scale occurs within the framework of macro-scale processes, and that it is supported by yet smaller micro-scale processes there is little cohesive theory linking the scales.

Micro-scale

Micro-scale processes can be considered to cover a wide range of perspectives on various aspects of design activity. Recent themes in this area include physiological measures for understanding design behaviour and cognition e.g. eye tracking for understanding both users (Wickman, Wagersten, Forslund, & Söderberg, 2014), and designers behaviour (Boa, Hicks, & Nassehi, 2013; Matthiesen, Meboldt, Ruckpaul, & Mussgnug, 2013). Other examples include the effects of different modes of communication in design interaction (Maier & Kleinsmann, 2013; Visser & Maher, 2011), and group interaction and designer activity in various contexts e.g. creativity (Snider, Culley, & Dekoninck, 2013), design review (Murphy, Ivarsson, & Lymer, 2012), and problem solving (Dorst & Cross, 2001; McDonnell, 2012). Here, micro-scale studies typically establish external validity (Adelman, 1991; Gray & Salzman, 1998) by building links to the wider design processes through, logical argument, theory building or testing, and explanatory models or frameworks. Less commonly this can be achieved through independent validation via integration with theoretically cohesive macro and meso-scale research. Examples include Dorst's (2008) advocacy of explanatory frameworks, Sun et al.'s (2014) development of specific theory, and Cheng et al.'s (2014) use of logical linking arguments. However, one aspect that is a common challenge for all these approaches is direct validation through empirical data. This is primarily due to the extremely time consuming nature of recording and analysing detailed behavioural or cognitive protocols.

This leads to the overall problem where it is difficult to cohesively compare and integrate findings from different scales of design activity. This results in two wider issues in the investigation of design activity. First, internal validity (Gray & Salzman, 1998) is negatively impacted because, although causal relationships can be established at each scale individually, establishing them across scales is significantly more difficult. Second, causal construct validity (Gray & Salzman, 1998) is negatively affected because there are few recognized models linking the concepts being studied across scales. As such, the presented study seeks to address these issues by presenting a multi-scale analysis of design activity and linking the scales in a single cohesive framework.

2 Method

Given the scope of this work, an observational approach was selected for two reasons. First, this approach complements and extends the scope of recent investigations of engineering design practice (Lethbridge et al., 2005) using, for example, work sampling and email logging approaches (M. A. Robinson, 2010; Wasiak et al., 2010). Second, it provides for a rich insight into modern engineering design practice.

2.1 Description of Context and Population

This section describes the overall context of the study as well as the subsequent selection of the population. Here context is used to describe the situation in which the study was carried out i.e. the company, its external influences, and its internal structures. The company used for this study was a Small to Medium size Enterprise (SME). An SME was selected due to their predominance in the European economic environment (White, 2011). In terms of the major external influences on the company, it was UK based and had a typical annual turnover of circa £1,000,000. Further, it had over forty years of experience in its current market and deep, long-standing ties to both a university and a hospital as primary collaborators. In terms of internal structures, the company hierarchy was relatively flat, with junior and senior practitioners mixing and working together. There was also a strong culture of relative informality in terms of hierarchy with well-attended group breaks and social events.

Given these factors, the selected company was considered to provide a relevant case for SME level engineering design research, whilst also providing a complementary sample to that used in other recent studies of engineering design processes, such as, studies by Robinson (2010) and Wasiak et al. (2010).

The company population included seven engineers and eleven other management and support staff. Sample selection was restricted to those engineers currently active on engineering design projects (7). The identified practitioners ranged in age from 25 to 40, however, they were otherwise similar in terms of socioeconomic characteristics, education (at least Masters level degree in a relevant engineering topic), and background. Relevant experience was distributed evenly with age (ranging for 1 to 17 years). Based on this assessment a sample size of three was selected in order to effectively cover the various perspectives represented across the engineer population in the company. Selection was carried out in two steps. First, volunteers were asked for (due to the in depth data recording) and then three participants were randomly selected from this subset. This resulted in one junior, one midlevel, and one senior engineer. Although a fully randomised selection regime would have offered the best possible approach (Torgerson & Torgerson, 2003), this was not pragmatically possible due to the level of observation involved.

2.2 Setup and Data Collection

The observation setup and subsequent data collection approach focused on generating a rich, multifaceted and overlapping dataset. This approach was selected in order to allow for both quantitative and qualitative analysis but also to ensure as complete a record of the study period as possible via redundancy (McAlpine, Cash, Storton, & Culley, 2011; H. Robinson, Segal, & Sharp, 2007; Seale, 1999). Further, the multifaceted approach allowed for the full range of engineering design activities to be recorded. The primary means of data collection were stationary cameras recording each participant's workspace and personal activity, synchronised with a screen capture recording of their computer. This was complemented by a mobile camera worn by the participant, and a live record of the participants' logbook activity. This allowed for capture of activity at the normal workstation and in meetings or other situations away from the desk, and ensured that at least two complementary sources captured each activity. Finally, a work diary was used to note activities not recorded by the technical setup. The capture approach is summarised in Table 1. Overall 100 hours of video (not including the multiple streams) was generated – approximately one working week for each participant.

Table 1: Summary of data collection

Engineering activity	**Approach**	**Overview and reference**
Collocated meetings and collaboration	Recording of logbook	Meeting notes and audio of conversation
	Mobile camera	Audio and video from the participants perspective
Written communication	Screen capture	E-mail and other messaging activity via computer
	Work diary	Other messaging activity
Distributed communication	Workspace cameras	Audio and visual of phone or computer use
	Screen capture	Computer based video conferencing
Individual design work	Recording of logbook	Personal note making/working
	Screen capture	Detail of work carried out on computer
	Data logging	Overview of computer usage
Project management activity	Screen capture	Detail of work carried out on computer
	Data logging	Overview of computer usage
Participant detail	Workspace camera 1	Visual of participant demeanour
	Workspace camera 2	Audio and visual participant demeanour
Other	Work diary	Identifies events not otherwise recorded

2.3 Study Implementation

The study itself consisted of three phases for each participant: acclimatization, study, and post-study. In this context study effects can have a significant impact (Adair, Sharpe, & Huynh, 1989; Falk & Heckman, 2009; Holden, 2001; Kazdin, 1998). To mitigate their influence researcher/participant interaction was minimised throughout, and an acclimatisation phase was introduced. This allowed the participant to return to as close to normal behaviour as possible before the start of the main study phase (Barnes, 2010; Leonard & Masatu, 2006; Podsakoff, MacKenzie, Lee, & Podsakoff, 2003). Further to reducing study effects the acclimatisation period allowed the participants to become familiar with the observation setup, adaption and checking of data recording procedures, and the gathering of participant feedback on the perceived effectiveness of the capture strategy. Such reflective feedback is a key tool for improving rigour (H. Robinson et al., 2007). In total this period lasted three weeks for each participant, which was considered to be sufficient for return to normal behaviour based on the extant literature (Leonard & Masatu, 2006). The study phase then lasted one week for each participant. Participants were recorded independently and were not working on the same projects or otherwise formally interacting during their study periods. The post-study phase was used to validate the completeness and accuracy of the captured data (H. Robinson et al., 2007) using a semi-structured interview. This checked if the participants' perceived their working practices to have been, in any way, unusual during the study and allowed the participants to explain/expand on any incidents reported in the work diary.

2.4 Coding and Analysis

In order to facilitate the multi-scale analysis of the engineering design process the coding was split into a number of passes. In practice, data was synchronised and then all three participants were coded in series with four coding passes carried out immediately after each other. Each pass described one aspect of the engineering design activity and gradually increased in detail whilst also allowing periods not relevant for further analysis to be removed e.g. lunch breaks, or personal activities. This builds on the Activity Theory conception for this work discussed in Section 2.

The four passes covered: situational context, engineering subject, interactions, and subject, defined below and summarised in Table 2:

- **Situational context** – the current work environment and the focus of the work with respect to the engineering design process (Hales, 1987; Ulrich & Eppinger, 2003).
- **Engineering subject** – the engineering design specific characteristics of the exchange between subjects: problem solving and information (Blandford & Attfield, 2010; Wasiak et al., 2010).
- **Interactions** – the object(s) forming the primary focus of the activity, both individual and group.
- **Subject** – the characteristics of exchanges: type of information, personal interactions and mutual understating (Bedny & Harris, 2005; Horvath, 2004; Wasiak et al., 2010).

These areas have been designed to fulfil the key requirements for understanding and contextualising activity as defined by Activity Theory (Bedny & Harris, 2005): object (a tool or material object which the subject or group of subjects interact with), and subject (two or more subjects are characterised in terms of information exchange, personal interactions and mutual understanding). Each pass was split into groups. Within each group codes are mutually exclusive.

Table 2: Summary of codes used to describe engineering design activity

Pass 1 Situational context			
Group	**Nº**	**Code**	**Code options**
Interaction 1	1	Individual/ group	0 - individual, 1 - group
Interaction 2	2	Synchronous/ asynchronous	0 - synchronous, 1 - asynchronous
Interaction 3	3	Co-located/ distributed	0 - co-located, 1 - distributed
Environment	4	Location	0 - normal, 1 - other
Focus 1	5	Design process stage	1 - brief creation, 2 - feasibility, 3 - design development, 4 - manufacture, 5 - testing, 6 - reporting, 7 - other
Focus 2	6	Focus: people / product / process	0 - other, 1 - people, 2 - product, 3 - process
Pass 2 Engineering subject			
Group	**Nº**	**Code**	**Code options**
Problem solving	7	Goal setting	0 - not goal setting, 1 - goal setting
	8	Constraining	0 - not constraining, 1 - constraining
	9	Exploring	0 - not exploring, 1 - exploring
	10	Solving	0 - not solving, 1 - solving
	11	Evaluating	0 - not evaluating, 1 - evaluating
	12	Decision making	0 - not decision making, 1 - decision making
	13	Reflection	0 - not reflecting, 1 -reflecting
	14	Debating	0 - not debating, 1 - debating
Information exchange	15	Recognising need	0 - not recognising need, 1- recognising need
	16	Interpretation	0 - not interpreting, 1 - interpreting
	17	Validation	0 - not validating, 1 - validating
	18	Seek/ request	0 - neither, 1 - seeking, 2 - requesting
	19	Using information	0 - other, 1 - informing, 2 - clarifying, 3 - confirming
Management exchange	20	Managing	0 - not managing, 1 - managing
Pass 3 Interactions			
Group	**Nº**	**Code**	**Code options**
Audio-visual	21	Audio only	0 - not interacting with X, 1 - interacting with X
	22	Visual only	
	23	Audio-visual	
Documentation	24	Formal	0 - not interacting with X, 1 - interacting with X formal/informal (Hicks, Culley, Allen, & Mullineux, 2002)
	25	Informal	
Physical	26	Environment	0 - not interacting with X, 1 - interacting with X
	27	Tools	
	28	Design representations	
Pass 4 Subject			
Group	**Nº**	**Code**	**Code options**
Type of exchange	29	Opinion/ orientate/ suggest	giving or receiving: 0 – other, 1 – opinion, 2 – orientation, 3 – suggestion
Understanding	30	Agree/disagree	showing: 0 – other, 1 – agreement, 2 – disagreement
Personal 1	31	Antagonism/ solidarity	giving or receiving: 0 – other, 1 – antagonism, 2 – solidarity
Personal 2	32	Tension/ tension release	showing: 0 – other, 1 – tension, 2 – tension release

As with the coding, analysis was considered via a number of increasingly detailed passes. First, all the individual codes were considered to quantitative map out the crude characteristics of the observed activity. Second, codes were grouped in order to describe more complex engineering design activity. The grouping process was based on extant descriptions of important engineering design activities summarised in Table 3. Finally, detailed analysis was undertaken of important events and situations identified during the study period.

Table 3: Grouped codes

Engineering design activity	**Description**
Ideation	Group idea generation tasks inc. group brainstorming, idea selection, and idea development (Cash, Elias, Dekoninck, & Culley, 2012)
Concept development	Concept development tasks inc. individual brainstorming, concept exploration, and development (Kuijt-Evers, Morel, Eikelenberg, & Vink, 2009)
Design elaboration	Development of a design once a final concept has been accepted inc. design refinement and problem solving (Carrizosa & Sheppard, 2000; Kim & Maher, 2008; Luck, 2007)
Reviewing	Reviewing existing work or future planning inc. review meetings and reflection on current designs (D'Astous, Detienne, Visser, & Robillard, 2004; Huet, Culley, McMahon, & Fortin, 2007)
Technical embodiment	Technical layouts and CAD configurations inc. CAD, prototyping and configuration (Chenouard, Sebastian, & Granvilliers, 2007; Scaravetti & Sebastian, 2009)
Testing	Running, setting up or dismantling test hardware or software inc. technical testing and user testing activities
Project reporting	Formal collation and dissemination of structured reports inc. lessons learned, and presentations of findings (Haas, Weber, & Panwar, 2000; Wild, Culley, McMahon, Darlington, & Liu, 2005)
Information seeking	Searching for, requesting, synthesizing and evaluating information inc. searching, interrogation of records and making notes on found data (Hertzum & Pejtersen, 2000; King, Casto, & Jones, 1994)
Dissemination	Informal distribution of decisions, work plans or progress inc. informal email, interpersonal conversations and shared workspaces (Söderquist, 2006)

3 Results and Discussion

For the purpose of discussing the results with respect to the proposed triple-scale framework, the representativeness and generalizability of the results are first considered.

3.1 Representativeness and Generalizability

In terms of generality, it is first necessary to consider the distinguishing features of the participants, and the recorded data. In particular when considering the overall distribution of activities with respect to time there is a clear focus on the product. This is consistent with the product development focus of the company and the participants as noted in Section 2.1. This gives a good basis for exploring design activity, however, it constrains the scope of this work, as there is little people or process management evident. It is also important to note that the main design stages encountered during the study periods were *design development* and *feasibility*. Notwithstanding this, all participants engaged in reporting activities in complement to their product design work. This suggests that the periods recorded provide good insights into general design activity. Finally, all participants experienced both group and distributed working periods, consistent with normal design work in the SME setting. These results are detailed in Figure 2 for each of the participants

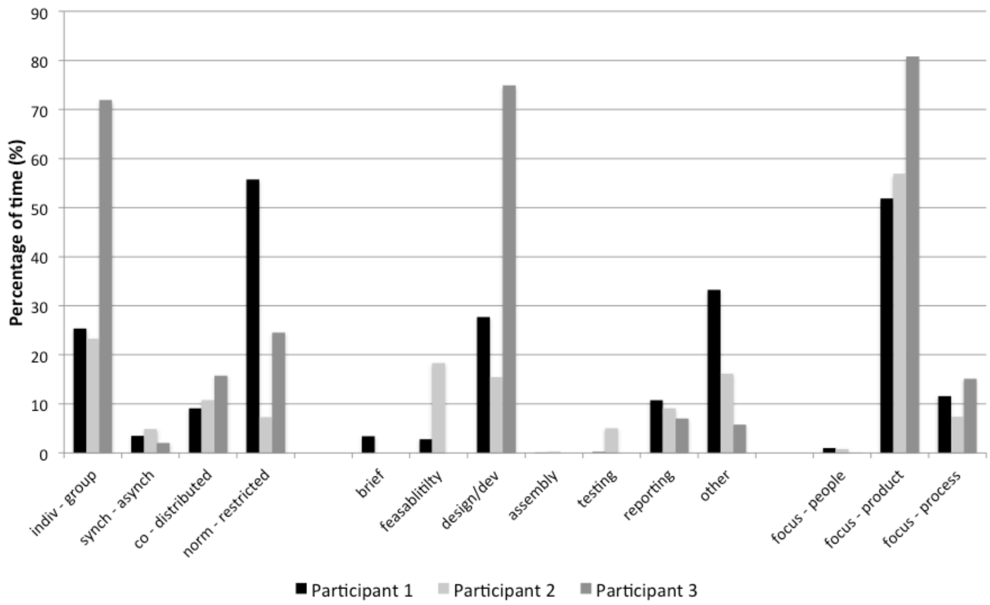


Figure 2: Distribution of working time with respect to the situation

To further explore representativeness the manifest problem solving and information exchange activities, described in Table 2, are further decomposed. From the range of information activities observed, seeking and interpreting stand out in the individual context while informing and clarifying are prominent in the communication context. This confirms the importance of information seeking activity (Aurisicchio, Bracewell, & Wallace, 2010; M. A. Robinson, 2010) and aligns with the expected importance of interpersonal information exchange (Lawson, Petersen, Cousins, & Handfield, 2009). In this regard these two types of information exchange – personal information seeking, and group information exchange – appear to be the primary information processes at work in the design activity (Hult et al., 2004)(*Authors*, XXXX). While this is further explored later it is important to highlight the correlation between previous studies and the results summarised in Figure 3.

With respect to problem solving three major elements emerge: solving, evaluation, and goal setting. This again corresponds with the extant literature, which describes design as a co-evolution of problem and solution (Dorst & Cross, 2001) – concepts closely related the manifest activities of solving and evaluation. There is also a distinct lack of constraining, exploring and decision-making activity. This re-enforces the interpretation of the recorded data as primarily associated with the design development process stage. To elaborate, at the design development stage major exploration tasks and constraints have already been established as opposed to the feasibility or conceptualisation stages (Wasiak et al., 2010). This is further nuanced by the high level of goal setting, suggesting that despite the product already being constrained and relatively well understood there is still a recurring need for goal affirmation and refinement as well as the setting of intermediary goals and tasks (Ulrich & Eppinger, 2003).

Based on the aforementioned results and their congruence with extant literature these findings, coupled with those in Figure 2, can be considered to partially validate the dataset as being representative of design work and suitable for further decomposition and comparison in line with the major aim of this paper.

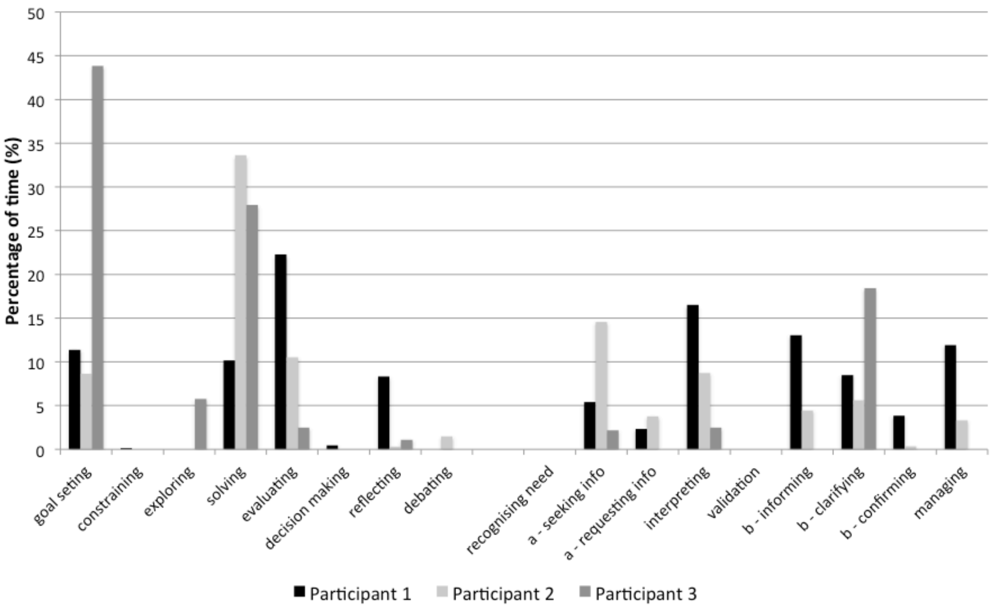


Figure 3: Distribution of working time with regards to problem solving and information codes

3.2 Macro-scale Processes

Macro-scale processes manifest themselves by virtue of two main mechanisms. First, there were periods of explicit activity that were directly associated with the various macro-scale processes. Second, there was a dynamic two-way influence between the macro-scale processes and the wider activities of the participants.

With respect to the former manifestation, there were a number of low frequency, high intensity, periods of activity that directly linked to macro-scale processes i.e. were specifically instigated by processes operating over a longer cycle than the typical day-to-day level of general design activity. For example, a stage gate review meeting would constitute a period of high intensity review activity explicitly instigated by a macro level process – in this case the stage gate design process (Ulrich & Eppinger, 2003). While these periods of activity are related to, and draw on, the day-to-day design work they are relatively distinct from surrounding activities, in terms of content and motivation. In this way these periods of activity provide a permeable link between the macro and meso-scales – with meso-scale processes being partially driven by and partially feeding into the macro processes. For example, the aforementioned stage gate review might result in the instigation of a number of information seeking, communication, and design development sub-processes but would not itself be the major defining factor in how these specific lower level processes played out.

These findings can be further explored with respect to the detailed data from each participant, shown in Figure 4. Here, Participant 1's activity could be associated with three parallel macro-scale processes. The first was a high level information processing cycle denoted by the information seeking (hours 4-10), and subsequent reporting periods (hours 10 and 12). The second was a low frequency reporting cycle denoted by the period between hours 27 and 31. Finally, there were two periods of design elaboration associated with a larger scale cycle in the progression of the design. This is characterised by the review (hours 12-14), and following design periods (hours 15-16, and 32-34).

With respect to Participant 2, fewer activities were identified that can be associated with macro-scale processes. However, a low frequency reporting cycle was again evident (hours 35 and 37). This was associated with the synthesis of a number of design elements being developed by the participant and others. As such, it denoted a distinct process in comparison to the other activities undertaken. Further, Participant 2 also displayed a wide range of activities across the board with elements of concept design, and testing embedded in the wider process.

Finally, Participant 3 displayed a more iterative cycle of design, and concept development/ideation that was tied to the core design development process. Although this appears the most straightforward macro-scale process with a simple pattern of alternating activities, deeper analysis revealed a number of parallel meso level processes feeding into and drawing on this macro-scale cycle (Section 3.3).

Of particular note is that analysis of the three participants reveals cycles of wide-ranging, dynamic activity during the study. These are related temporally, in terms of subject, and in terms of flow of information. The results for all the participants are summarised with respect to the study timeline in Figure 4. Periods of activity directly associated with macro-scale processes are highlighted in red. Throughout this analysis meso-scale activity was identified as critically related to the macro-scale processes. As such, the next section explores the meso-scale in more detail.

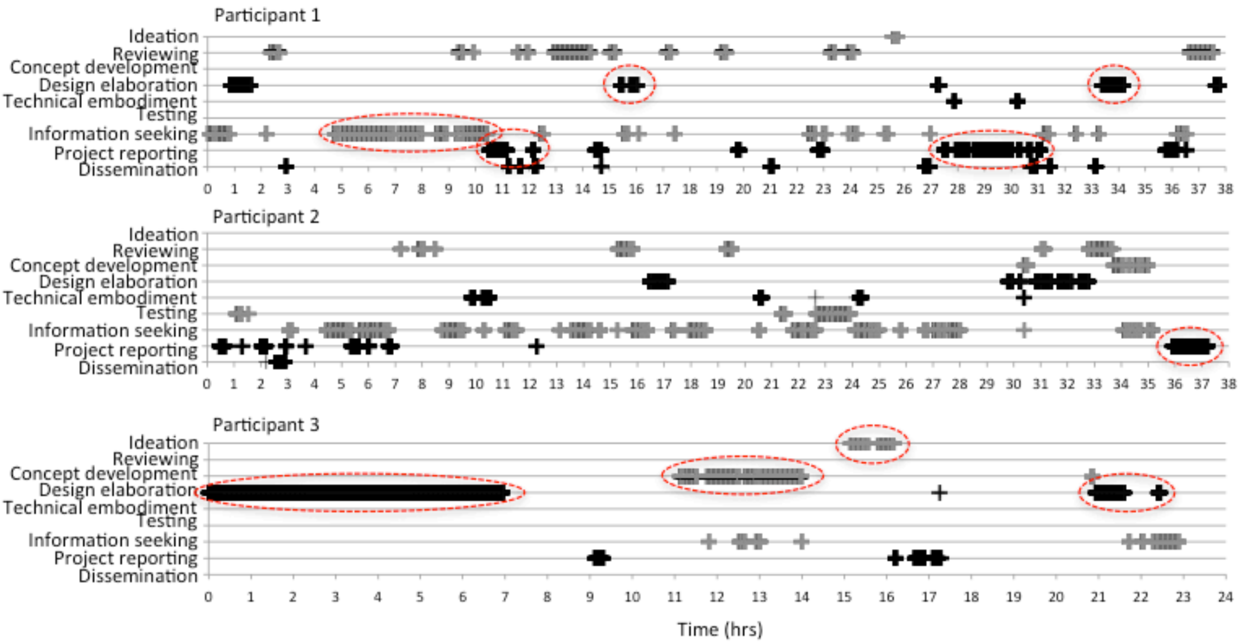


Figure 4: Macro-scale processes explicitly linked to periods of activity

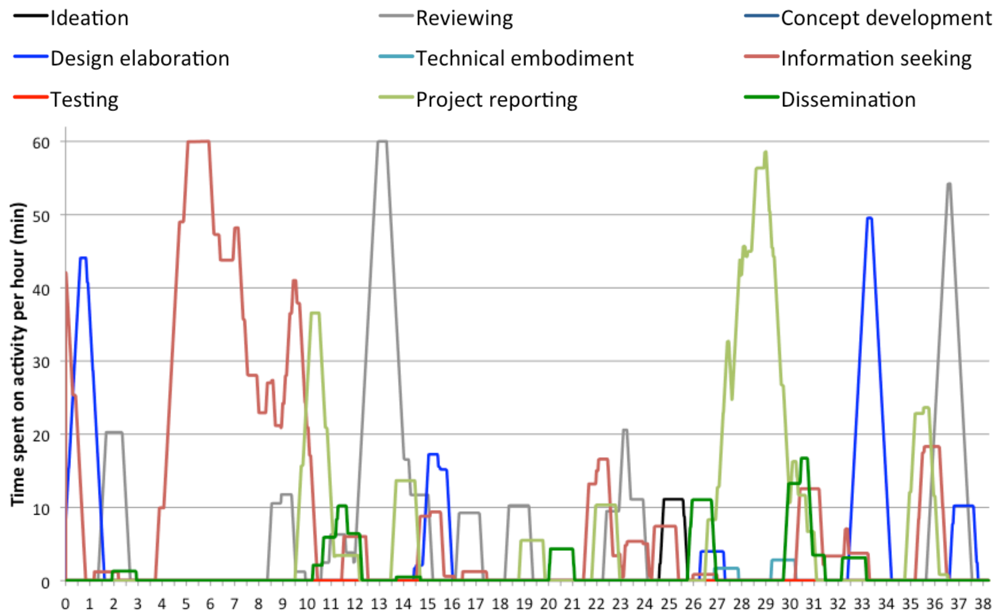
3.3 Meso-scale Processes

The range and magnitude of the different meso-scale activities over time for each participant is illustrated in Figure 5. Here, the focus is directed towards the high frequency (occurrence) low magnitude (intensity/time) cycles of activity, associated with meso level processes. In this context, there is a recurring focus on information processing, which appears to constitute the backbone of participant 1 and 2's work. Further, review and development activities are again related in terms of magnitude and sequence, with alternating periods of review and development. There is also further elaboration of the range and extent of activities undertaken during a single nominal design stage. Despite the overall process stage being design development, activities typically associated with other process stages e.g. *information seeking* and *testing* play critical roles in the activity profiles.

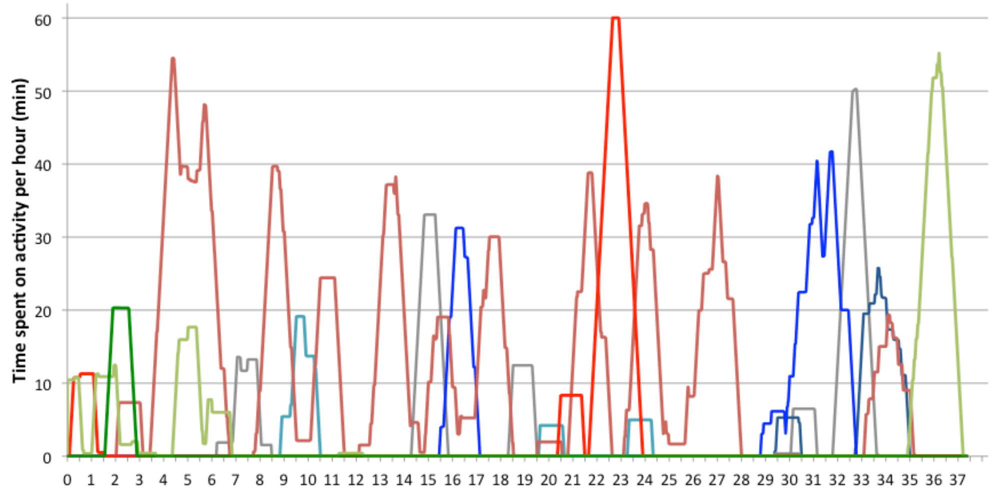
Considering Participant 1 (Figure 5a) a number of interlinked processes emerge from the analysis. These run in parallel, and have a range of frequencies. In particular, there is a low magnitude (10-20 minutes per hour) medium frequency (circa 6 hours) cyclical relationship between *information seeking/analysis*, and *reporting/dissemination*. This is distinct from the periods of activity of greater magnitude associated with the macro-scale processes. Similarly, *information seeking* appears to play a dominant mediating role in the activity of Participant 2 (Figure 5b). This is characterised by medium order magnitude activity (20-40 minutes per hour) with a frequency of circa 4 hours associated with both the main review and design activities. Although Participant 2 is distinct from Participant 1 the same process structures appear to be at play in both, with a complex, multilevel activity characterising the design work over the whole recorded period. Further, the dominance of the *information seeking/exchange* cycle is further clarified as parallel to the *problem/solution development* process linked to the design artefact.

Finally, in contrast to Participants 1 and 2, Participant 3 (Figure 5c) presents a less complex pattern of activity. However, two concurrent cycles can be identified in the data. In parallel to the macro-scale process there is an information seeking/reporting cycle (period circa 3 hours, magnitude 10-20 minutes per hour). This is significant as it directly mediates the larger scale process while displaying a distinct process internally independent from the macro-scale process. Here, the differences in overall complexity can be accounted for by the constrained nature of the participant's tasks during the observation period. In this case, they were primarily working on a single CAD drawing with a tight deadline. As such, there was a distinct focus on completing the main drawing, with other smaller tasks postponed by the participant. As such, although this case is significantly different in focus and character from the other participants it still shares the critical features identified throughout this work.

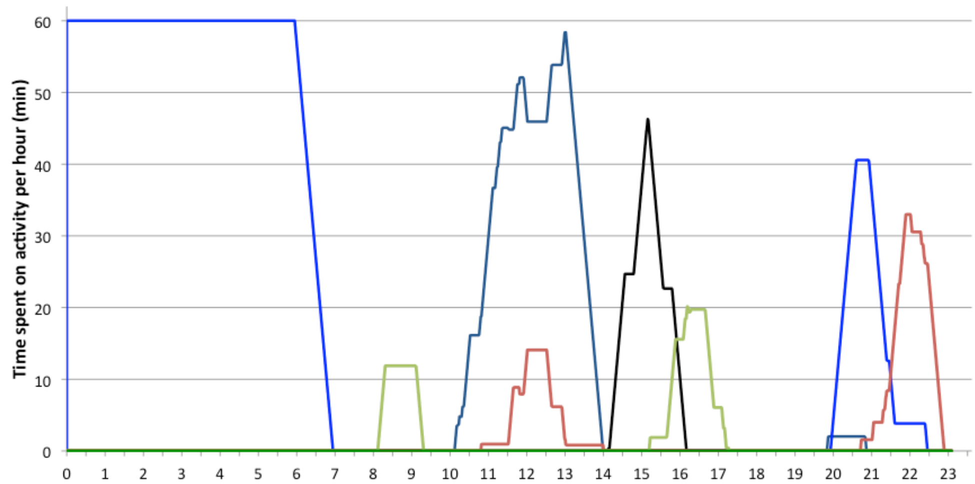
Concluding this part of the analysis the meso-scale results support the two important features identified in the macro-scale analysis. First, although the processes at the different scales exist in parallel they are distinct in their character, the magnitude of the activities, and their period of influence. Further, although the activities associated with the macro-scale analysis could be linked to large scale design process descriptions, such as, the stage gate model of Ulrich and Eppinger (2003), the processes evident at the meso-scale more readily link to models, such as, information processing (Hult et al., 2004), communication dynamics (Vande Moere, Dong, & Clayden, 2008), or decision making (Schmidt et al., 2001). Second, despite this difference in scale and associated theoretical models for describing the activity processes there is significant interrelation between scales. This leads to a picture of design activity as a complex fabric of interwoven processes at different scales, substantially greater than any one of the models mentioned previously. In this sense, macro-scale processes both drive and are driven by meso-scale activity but critically do not dictate the nature of the meso-scale processes themselves. In order to finalise the exploration of this related-yet-distinct process conceptualisation micro-scale processes are considered in the next section.



5a: Participant 1



5b: Participant 2



5c: Participant 3

Figure 5: Meso-scale all 3 participants graphs

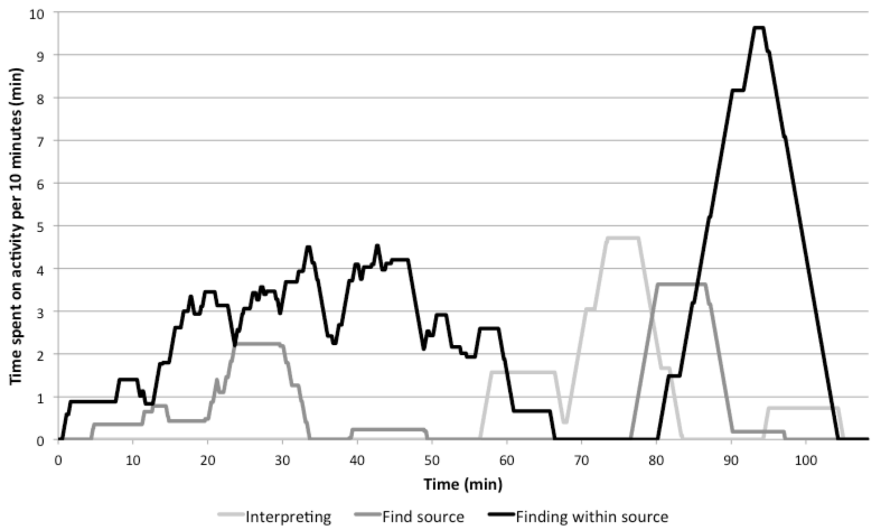
3.4 Micro-scale Processes

At the micro-scale, there is again evidence for processes which link to, but are distinct from, the macro or meso-scales. Here, activity can be further decomposed directly in line with the precepts of Activity Theory – which deals explicitly with this scale as realised in the Activity <-> Action <-> Operation framework (Section 1.1). This makes this scale the most comprehensively described both in a general theoretical sense and in terms of design activity e.g. problem solution iteration (Dorst & Cross, 2001). As such, this analysis focuses on further establishing the results from the macro and meso-scale analyses, as well as confirming the verisimilitude of the Activity Theory conception of activity at this scale. This latter element, in particular, serves to support the existing results and helps to confirm the proposed research framework describing design activity as a multi-scale interweaving of processes.

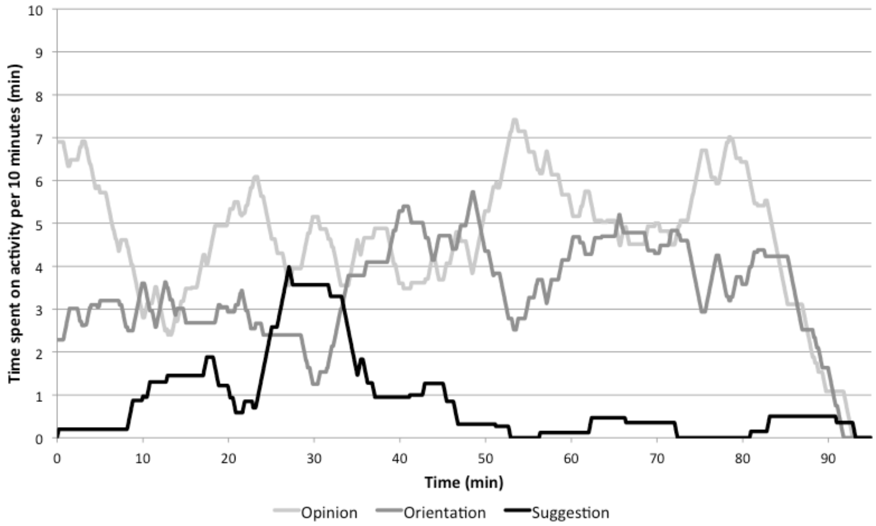
At this scale the results conform to the general tenets of Activity Theory. In particular the participants' behaviour can be described as a number of tasks occurring in series, which support and link to a number of activity processes occurring in parallel. It is these activities that then feed into the meso and macro levels. As an example of this sequential progression of tasks related to overlapping micro-scale activity cycles, Figure 6a details the information processing activities of Participant 1. Here, this can be linked to both organisational information processing theory (Hult et al., 2004) at the meso-scale or, further decomposed and related to cognitive information processing (Simon, 1978) at the micro-scale. This further links to the work of Robinson (2010) which explores the impact of information seeking at the macro-scale.

Finally, Figure 6b details the analysis of design review conversation at the operation level, focusing on the exchange of opinion. Here, the results support the previous multi-scale conception of design activity. In particular, the analysis highlights the micro-scale cycles of communication exchange that, although driven by the meso-scale activity, display their own distinct character in terms of process features, scale of event, and influences. This is further supported by Figure 6c that shows the same micro-scale opinion exchange processes but for a different activity – in this case ideation. Comparing these two examples reveals similarities in the interplay between the exchanges of opinion at the micro level despite being driven by distinctly different meso level activities.

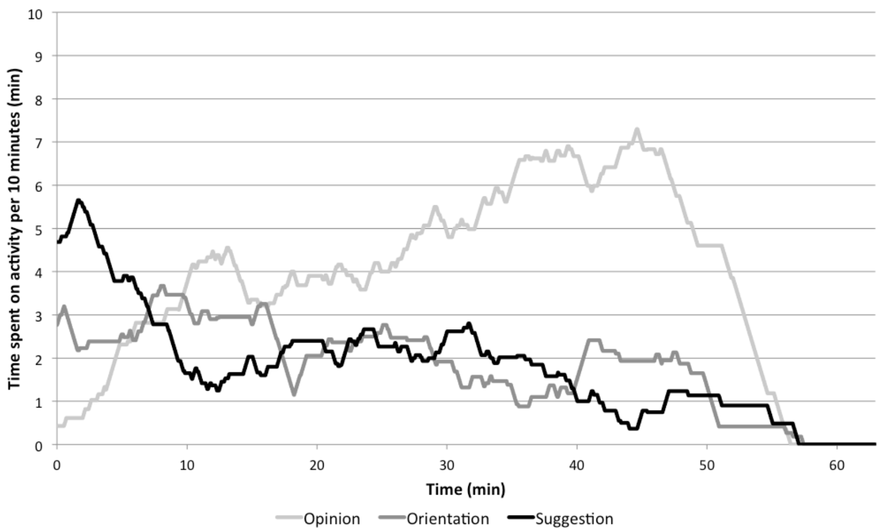
Bringing this together, there are a number of important implications for design researchers explored in the next section.



6a: Information processing activities carried out by Participant 1 (hours 7-9)



6b: Opinion, orientation, and suggestion exchange during a review meeting attended by Participant 1 (hours 12-14)



6c: Opinion, orientation, and suggestion exchange during an ideation session meeting attended by Participant 3 (hours 14-16)

Figure 6: Examples of micro-scale processes

4 Implications and limitations

This section outlines the major implications, and limitations of this work, and answers the driving question posed in the introduction: *how are the various scales of design activity related i.e. how do micro-scale structures link to macro, and possibly meso-scale structures?*

4.1 Implications: A New Perspective on Design Activity

There are several key findings and subsequent implications associated with the presented results.

First, the analysis highlights the layered nature of the processes affecting design activity. These are reflected at each scale, and constitute a number of aspects of design work that both interact and exist in parallel. Critically these appear to affect activity across scales. However, describing this theoretically is still a significant challenge, even given the layered conception offered by Activity Theory (Figure 1). Although previous authors have highlighted individual processes as drivers of design activity, this analysis shows that design activity is instead related to a number of parallel processes, with interrelations both internally and with respect to the wider design process.

Second, at the macro-scale, the design process has been typically divided into stages, suggesting monolithic blocks of certain activity types. Instead the results highlight that stage boundaries are fuzzy with activities from all aspects of design work represented. As such, it is perhaps more fitting to describe a stage with respect to a distribution of activities where, during the relevant stage, there is a predominance of one or possibly two major types, e.g. conceptual design and ideation during the early design stages. This has implications for how design work is supported throughout the design process and emphasises the importance of efforts to address aspects of design work at stages where they are not the primary function e.g. Snider et al.'s (2013) work on creative activity in the later stages of the design process.

Third, the multi-scale manifestation of a number of linked, parallel processes suggests that the search for a monolithic theory able to coherently describe and explain all aspects of design activity is perhaps premature. This is particularly the case given the relative immaturity of formal design theory. Instead the results highlight a number of distinct processes, which could more feasibly be addressed by focused theoretical contributions. These could then be linked through frameworks such as that proposed by Activity Theory or other as-yet undefined design specific models. For example, there has been significant work on problem evolution and its link to design activity (Dorst & Cross, 2001; Hatchuel & Weil, 2003), but other processes such as information processing, and communication have received relatively little attention in terms of formal models in the design specific domain. As such, identifying relevant theoretical models for this wider group of processes e.g. Information processing theory (Siebdrat et al., 2013), may pave the way to richer description of design as a cohesive process. This multi-scale nature of design and the interrelationships are depicted in Figure 7, which builds on the research framework developed from Activity Theory and described in Section 1.1.

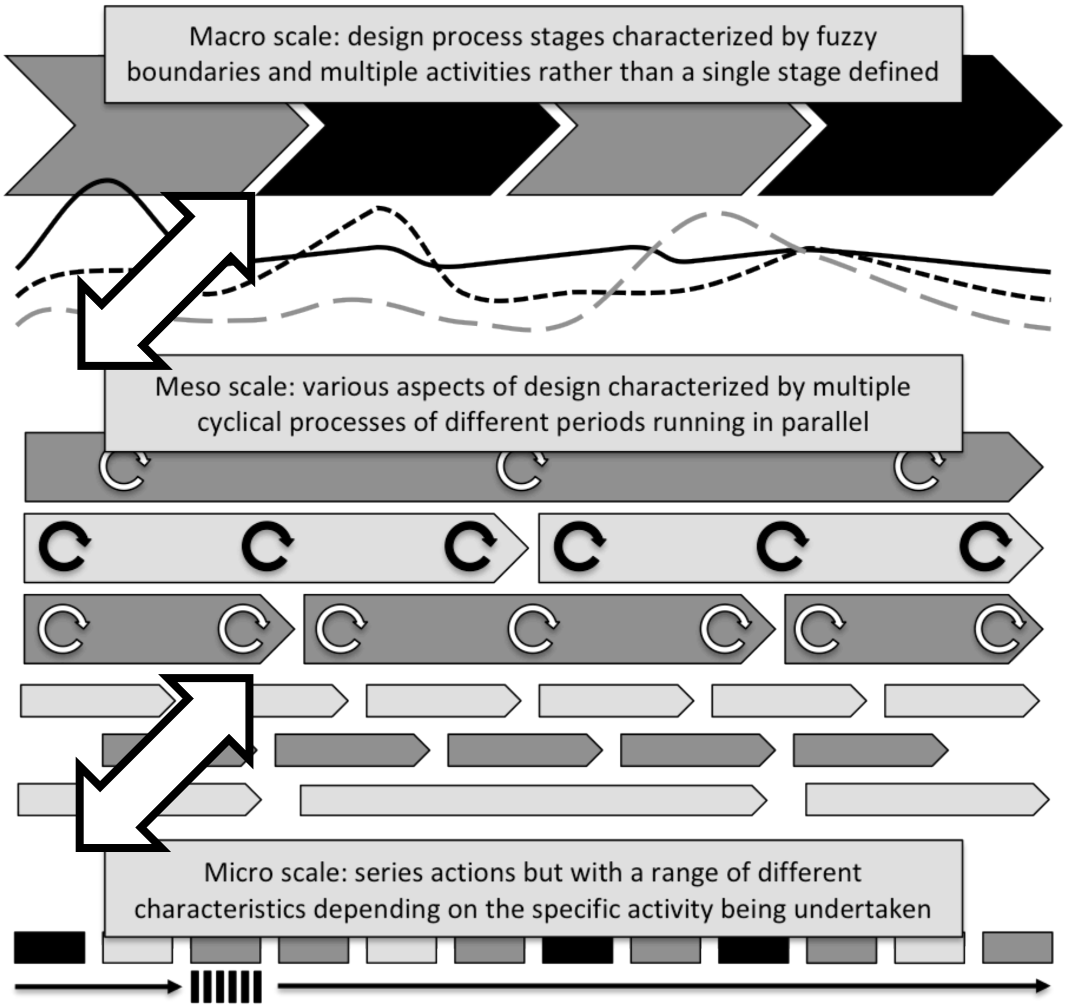


Figure 7: Reflecting on the multi-scale framework for describing design activity

In a more pragmatic sense these findings suggest two key implications for industry.

First, that design support needs to be able to address the interlinked nature of the activities involved. As such, it is not enough to simply support one aspect, such as, communication. Instead a suite of relevant tools should be used and carefully aligned based on reflective practice and explicit awareness of the multiple processes involved. In particular, consideration should be given to the different periods displayed by the various processes – implying different types of appropriate intervention.

Second, design process models hide the fact that all aspects of design activity are represented throughout the process and, as such, should be supported throughout. In particular this suggests that effective design support should be developed for the full range of activities and deployed on a weighted bases. This also highlights the need for further work on aspects of design activity support not typically associated with the given stages of the design process e.g. late stage creativity tools.

4.2 Limitations

The first limitation to mention here is that although team level interactions were observed in the data they were not the primary focus of this analysis. For example, each participant was recorded during periods where they were working directly with a team, but this activity was only coded from their perspective. Although this is not a confounding element with regards to the claims being made, a logical extension of this work would be to carry out a similar analysis on a team where each member is recorded simultaneously over a period of time.

The second limitation of the study was the size of the sample. Specifically, in order to fully validate the findings, it would be necessary to examine a larger number of participants across varied contexts. Although, the results presented here align with extant literature at both the macro, and micro-scales there is significant scope for further exploration of the interrelation between the various processes via further investigation of multi-scale designer activity. Further, by assessing a larger sample of situational contexts, a more detailed picture could be developed of what variables are most important for the different processes and how these are related across the scales.

Finally it is important to clarify the coding process for reliability assessment. In this case due to the amount of coding required (over 100 hours of raw footage, and five times that in coding time), and the sensitive nature of some of the captured footage it was not possible to carry out a full dual coding of the data. Instead the following procedure was applied (*Authors* XXX):

1. The coding schema was established based on known sources.
2. A small period of video was then coded by the main author, and another researcher not involved with the project. This was used to repeatedly check agreement, and refine schema until 100% agreement was reached.
3. Once finalised the schema (as described in Table 2) was used to code the whole dataset with participants in a randomly assigned order.
4. Finally, once complete the first portion of footage was coded again to check for drift over time (Taplin & Reid, 1973). This resulted in a 91% point by point agreement which is above the 80% threshold set by Kazdin (1982).

5 Conclusions

This work has identified and started to address the gap in research associated with bridging the macro and micro-scale processes in design activity. In order to investigate this an observational study was explored using a detailed protocol analysis.

The study confirmed and aligned with the extant literature on the expected macro and micro-scale structures of design work. However, it offered significant new insight on the relationship between these features and the interplay between the various processes involved. Here design activity was found to align with no single process but instead constitute a number of parallel interrelated processes, including problem/solution development, and information seeking and exchange, which occur over three scales: micro-, meso- and macro-. Further, these processes were found to manifest at a number of scales and with varying periods and magnitudes of activity.

These findings have some significant implications for the development of design theory. In particular they point to the need for a number of complementary theoretical models in order to cohesively describe the complex multi-faceted interweaving of processes. Further, the distribution of activity highlights the fact that all aspects of design are represented across the design process stages and thus has implications for how researchers target design support tools.

This also points to future research opportunities. In particular there is a need to further explore and decompose the various processes and their manifestation at the different scales of analysis. This should also be accompanied with design specific theory building. Explicitly targeting areas beyond the design artefact itself, and considering addition or development of models relating to, for example, design information processing communication, and decision-making. There is also scope for expanding the link between micro-scale design activity and macro-scale manifestations of its affect in the wider design process.

Although there are a number of limitations associated with this work the findings presented here hold significant implications for both design researchers, and those seeking to support design in practice. Finally, we conclude by suggesting that the new perspective developed by this study linking activity across scales gives a major opportunity for developing a richer more cohesive body of formal design theory, and expanding and linking together the current body of theory in design and its related fields.

Acknowledgements

TEXT IN FINAL VERSION

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