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Activity Theory as a means for multi-scale analysis of the engineering design process: A protocol study of design in practice

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Abstract

This paper contributes to improving our understanding of design activity. Specifically the paper uses Activity Theory to enable a multi-scale analysis of the activity of three engineering designers over a period of one month. Correspondingly, this paper represents the first work that explicitly investigates design activity across different scales, referred to as macro-, meso- and micro-scales. In addition to establishing the range of activities and tasks that occur at, and constitute, each scale the underlying relationships between the scales of activity are discussed. Further, the paper elucidates the wider implications of the proposed framework and its findings for both design research and practice. Central to these implications is the articulation of design as a complex fabric of interwoven processes.

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. This is further supported by the importance of Activity Theory in the study of human behaviour (Bedny & Harris, 2005), and the concept of multi-level theory building in the management domain (Klein, Tosi, & Cannella Jr, 1999). 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 questions for this paper: *At what scales do distinct design activities and tasks exist and how are the various scales related?*

In order to explore this question, the work develops a multi-scale analysis approach based on Activity Theory. This is applied to a protocol study of design in practice. Specifically, a fine grain protocol analysis is used to describe a longer period of design activity in order to facilitate analysis at different 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 different 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 different scales of design activity and their interrelationship, two areas need first to be considered. These include how the different scales can be coherently considered in a single theoretical framework, and second, understanding how the different scales have been treated to date in design research. These two dimensions are considered in the following sections.

1.1 Multi-Scale Activity

Design work can be described at a number of different scales, from cognition to the overall progression of the design process (Bucciarelli, 1988; Cross & Cross, 1995; Dorst & Cross, 2001; Gero, 1990). Further, while it is accepted that there is a strong relationship between these different scales, the nature of the relationship is not fully understood. For example, there is an expectation during the concept development phase that the designer will engage in smaller scale ideation behaviour. However, there is no framework for describing design work across scales within the design literature. Thus, it is possible to consider more general theory. Here, Activity Theory stands out as highly relevant to the multi-scale phenomenon of design work as described above (Bedny & Harris, 2005; Jonassen & Rohrer-Murphy, 1999; Leont'ev, 1978). This theory has started to be recognised in the design domain (Moser, Ziegler, Blessing, & Braukhane, 2012; von Saucken, Schroer, Kain, & Lindemann, 2012), although it is not yet widely used.

Activity Theory describes work as a system of embedded elements from activity down to cognition (Bedny & Harris, 2005; Bedny & Karwowski, 2004; Jonassen & Rohrer-Murphy, 1999). For the purpose of design, Activity Theory can be used to decompose work into three distinct levels:

1. ***Activities*** are defined as a goal directed system where cognition, behaviour and motivation are integrated (Bedny & Karwowski, 2004). Activities can be identified with respect to an overall motivation, and are associated with a number of conceptually linked tasks. An example activity is the development of a new design concept.
2. ***Tasks*** are defined as a logically organised system of actions required to achieve a goal under specific conditions (Bedny & Karwowski, 2004; Leont'ev, 1981). A task can be identified with respect to the completion of specific goals, and corresponds to a number of temporally linked actions. These goals are aligned with the motivation of the associated activity as well as across

related tasks. An example task is the generation of ideas in a brainstorming session, which in combination with other related tasks contributes to the activity of concept development.

3. ***Actions*** are defined as discrete parts of a task that fulfil intermediate, conscious goals (Bedny & Harris, 2005). Actions can be identified with respect to the completion of specific sub goals required to complete a task, and correspond with a temporally linked lower level elements. An example action is recording a single idea on a whiteboard as part of a brainstorming task.

Although further decomposition is possible through Activity Theory, this focuses on unconscious operations at the cognitive level and is thus beyond the scope of this work. Activity Theory describes a framework where Activity, Task, and Action form a layered description of any period of work. Using the above example, the designer is simultaneously recording an idea (*action*), as part of the brainstorming session (task), contributing to the wider development of the new design concept (*activity*). As such, Activity Theory allows for multiple parallel and serial elements to be considered in a cohesive manner. These three concepts, activity, task, and action, provide a lens through which a unified description of design work can be articulated, particularly where there is sparse theory. In particular Activity Theory is used here because it provides:

- A cohesive relationship between levels of activity. Through examination of the inter-relationship between activity levels, it is possible to elicit key influences, and thus describe the structure of activity performed in any design case.
- A holistic description of design work that can be used to cohesively describe activity across hierarchical levels while maintaining traceable relationships between each. In comparison, no extant framework applied in engineering design describes activity at multiple levels.
- A framework for describing parallel, embedded streams of activity, thereby supporting the integration of complex design work. This also allows for an understanding of the effect of embedded parallel and serial processes.

Further, it is possible to conceptually expand the *activity – task – action* framework in order to describe groups of activities, in a similar manner to how actions are grouped into tasks (Bedny & Harris, 2005). In the context of design, this allows for a more cohesive description of design work to be proposed i.e. linking the cognitive level to large-scale groups of activities, and ultimately 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, it is possible to build on Activity Theory to specifically address a design process perspective. This allows for the description of process features with respect to three levels: groups of activities, groups of tasks, and groups of actions. In order to separate this process perspective from the elemental definitions of Activity Theory we adopt the following process nomenclature: macro, meso, and micro-scale. This allows these design process scales to be defined with respect to theory whilst also retaining the ability to describe complex design work. This results in the following parallel framework associating the process scales and Activity Theory:

Groups of Activities ←→ Groups of Tasks (Activity) ←→ Groups of Actions (Task)

Macro-scale processes ←→ Meso-scale processes ←→ Micro-scale processes

Focusing on recognised descriptions of design work this is then distilled into the triple-scale research framework illustrated in Figure 1. Further it is now possible to rigorously define each of the processes levels in generalised terms:

- ***Macro-scale processes***: sequences of activities linked by a common focus e.g. coordinating the design work of a team across the development of a new product.
- ***Meso-scale processes***: sequences of tasks linked by a common motivation e.g. distribute research and development findings to the design team.
- ***Micro-scale processes***: sequences of actions linked by a common goal e.g. compile a design report.

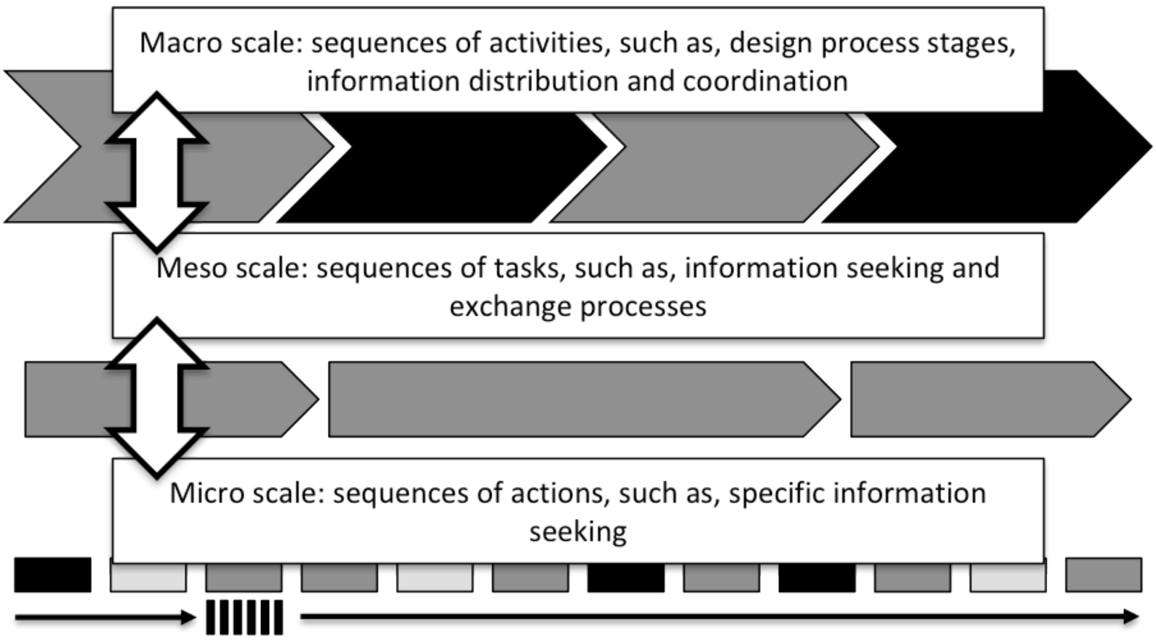


Figure 1: Research framework showing the embedded macro, meso, and micro-scale processes

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 that links or bridges the 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 across the whole design processes: sequences of activities linked by a common focus e.g. coordinating the design work of a team across the development of a new product. 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). Here, 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). This can be further observed in concept design. Here, it is expected that during the concept development phase, designers carry out specific ideation activities. Conversely, these activities partly define and drive the progression of the concept development phase. Thus, theoretically linking these process scales. However, 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 (M. A. Robinson, 2010), e-communication patterns (Wasiak et al., 2010), and the use of engineering documents (Wild, McMahon, Darlington, Liu, & Culley, 2010): sequences of tasks linked by a common motivation e.g. distribute research and development findings to the design team. Here, methods focus more on groups of tasks 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 is embedded within 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: sequences of actions linked by a common goal e.g. compile a design report. 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. This is primarily due to a lack of guiding theory and the increased complexity of the datasets involved, which can introduce bias or other confounding variables. 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 workforce 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 focused on one aspect of the engineering design activity whilst also allowing periods not relevant for further analysis to be removed e.g. lunch breaks, or personal activities. This builds up a rich picture of the participants' activity, which can then be analysed with respect to each process scale: macro, meso, and micro, based on the Activity Theory framework introduced in Figure 1.

Here, it is important to emphasise the embedded nature of the processes i.e. at any moment, activity can be simultaneously associated with processes at each scale. As such, the coding builds up a body of information relevant to all levels of activity: groups of activities, groups of tasks, and groups of actions. Specifically, the four passes coded for: 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).
- **Interaction type** – the object(s) forming the primary focus of the activity, both individual and group.
- **Subject type** – 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). As such, the body of coded data can be used to inform all process scales. For example, consider the three simultaneous processes: developing a new concept (macro-scale), generating ideas (meso-scale), and communicating a specific idea (micro-scale). The codes in Table 2 inform each scale as follows. The situational context elements of 'Focus' (Pass 1) are used to identify the macro-scale *concept development process*. Next, the meso-scale *ideation process* is identified by the 'interaction' elements of the situational context (Pass 1), the engineering subject (Pass 2), and interaction type elements (Pass 3). Finally, the micro-scale *communication process* can be identified from the engineering subject (Pass 2), interaction type (Pass 3), and subject type (Pass 4). As previously mentioned, for the purpose of coding the data, each pass was split into groups comprising groups of codes that are mutually exclusive.

Table 2: Summary of generic 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 - not using information, 1 - informing, 2 - clarifying, 3 - confirming
Management exchange	20	Managing	0 - not managing, 1 - managing
Pass 3 Interactions type			
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 type			
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

It is also important to clarify the practical 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 (Cash, Hicks, Culley, & Adlam, 2015):

1. The coding schema was established based on known sources.
2. A small period of video was 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. Lastly, 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).

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. 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

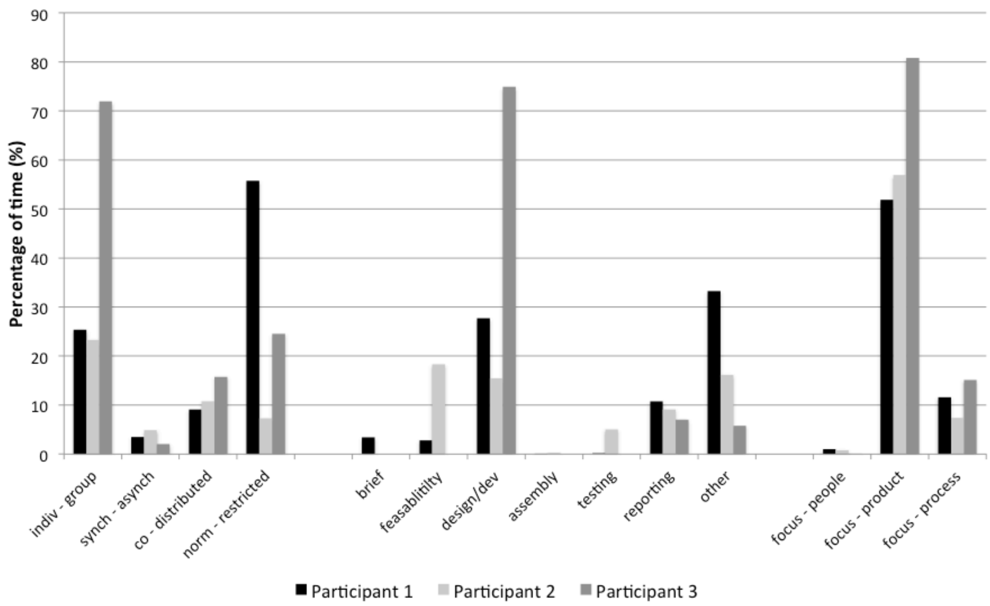


Figure 2: Distribution of working time with respect to the situation

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). 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 support the external validity of the dataset as being representative of design work and suitable for further decomposition and comparison in line with the major aim of this paper.

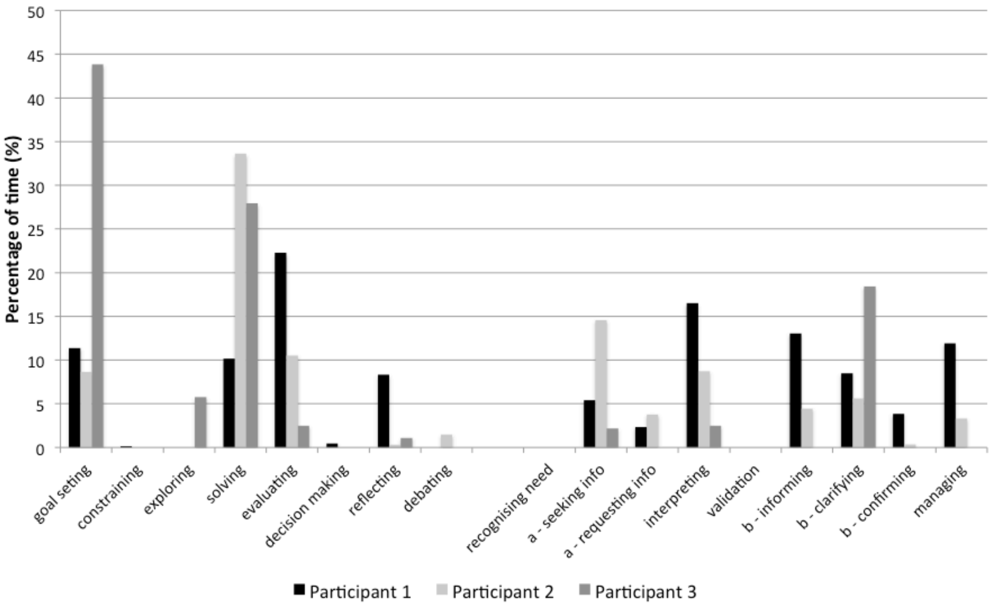


Figure 3: Distribution of working time with regards to problem solving and information codes

3.2 Macro-scale Processes

Macro-scale processes were identified with respect to the framework defined in Section 1 i.e. related groups of activities linked by a common focus. These were identified in three steps. First, the codes related to situational context (Pass 1, Table 2) were used to identify every activity type found in the dataset. Each type constituted a unique combination of the focus codes (combinations of 'focus 1' and 'focus 2' code options), resulting in 12 types. Next, these were grouped by similarity to form grounded categories of related activity types. These groupings were then consolidated by linking the grounded categories to key groups of activities described in the literature. Thus Table 3 summarises the groups of related activities, which were used to map out the macro-scale processes.

Table 3: Codes grouped at the macro-scale groups of activities level

Group of activities	Description
Product design	Activities associated with the stages of the design process (Ulrich & Eppinger, 2003)
Organisational information processing	Activities associated with information management such as archiving (Hult et al., 2004)
Personnel management	Activities associated with the management of human resources, including availability, training or other organisation (Wasiak et al., 2010)

Macro-scale processes manifest themselves by virtue of two main mechanisms. First, there were periods were the tasks being undertaken at the lower activity levels 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 activity of the participants through the embedded nature of the smaller scale processes.

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 associated with the progression of the larger scale processes. 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 product design process (Ulrich & Eppinger, 2003). While these periods are related to, and draw on, the day-to-day design work they are relatively distinct from the surrounding activities, in terms of content and focus. In this way these constitute periods of alignment when the smaller scale embedded processes can be directly linked to the macro-scale processes. This provides 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. This cross-scale linking is discussed further in Section 3.5.

These findings can be further explored with respect to the detailed data from each participant. Of particular note is that the design process is intertwined with informational processes. These are related temporally, in terms of subject, and in terms of flow of information. Further, personnel management played only a minor role in the participants work. The results for all the participants are summarised with respect to the study timeline in Figure 4. In order to further explore the flows of information between these macro-scale processes it is necessary to consider the meso-scale and the distribution of design tasks.

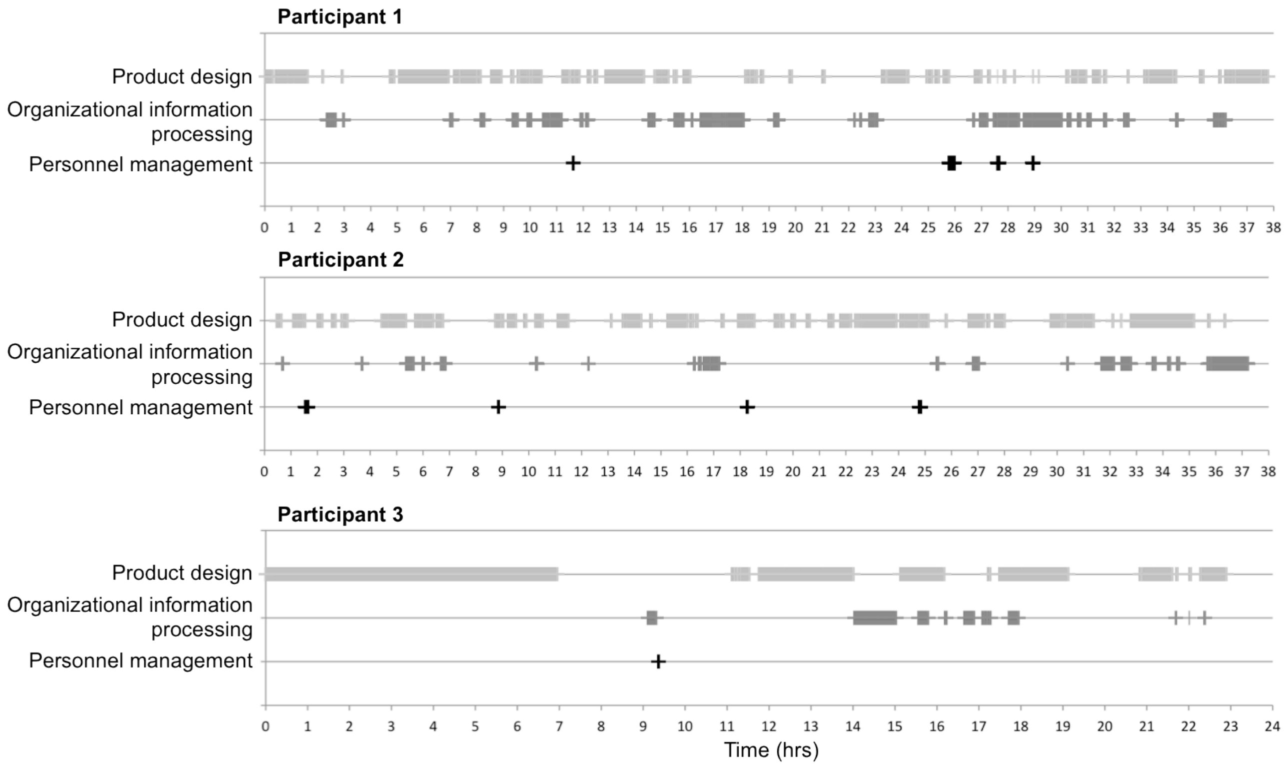


Figure 4: Macro-scale processes associated with groups of activities

3.3 Meso-scale Processes

As with the macro-scale, meso-scale processes were identified with respect to the framework defined in Section 1 i.e. related groups of tasks linked by a common motivation. Here a group of related tasks constitutes an activity. These were identified via a number of steps. First, the codes used to describe the task level (Passes 1, 2, and 3, Table 2) were used to identify every task type found in the dataset. Each task type constituted a unique combination of the codes from Passes 1, 2, and 3, resulting in 147 types. Next, these were grouped by similarity to form categories of related task types. Finally, these groupings were consolidated by linking the grounded categories with design theory. These groupings were exhaustive with respect to the data dealing with engineering design work. Although personal activities and miscellaneous work, such as, making tea for a meeting were coded they are not included here. The activities summarised in Table 4 describe the groups of related tasks (activities), which were used to map out the meso-scale processes.

Table 4: Codes grouped at the meso-scale activity level

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)

The range and magnitude of the different meso-scale activities over time for each participant is illustrated in Figure 5. As described in the Section 3.2, these are primarily embedded within the macro-scale design and organisational information processes. In this context, there is a recurring focus on information seeking and evaluation, which constitutes 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.

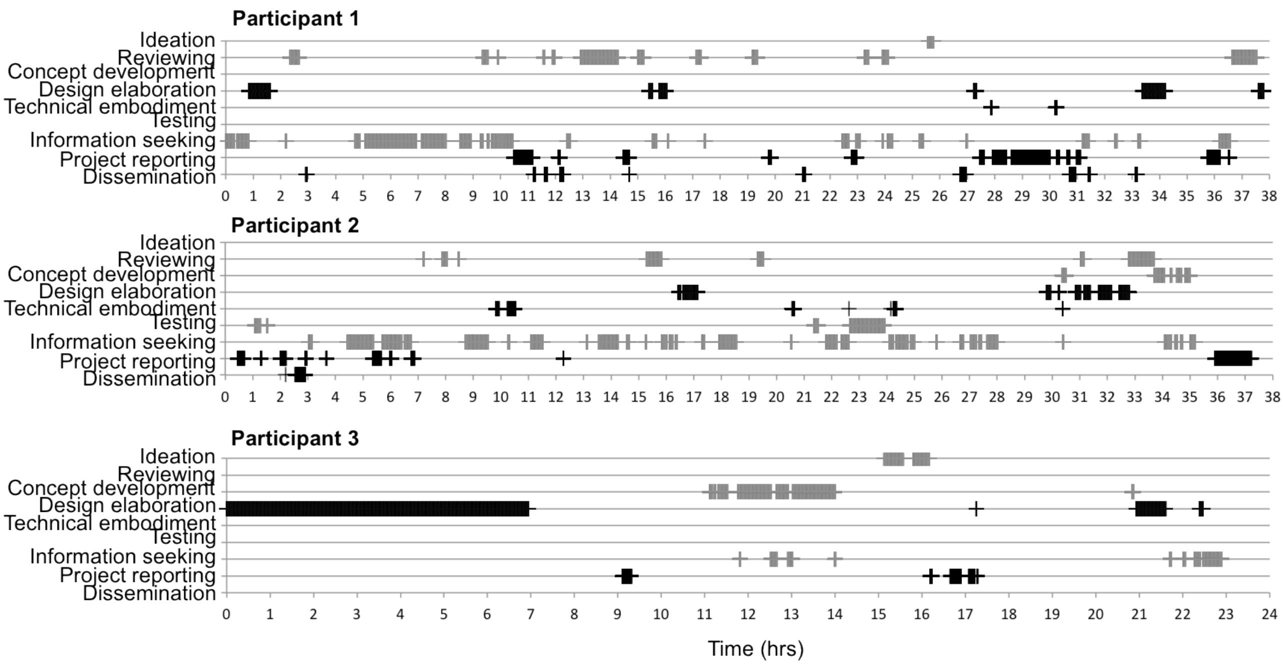


Figure 5: Meso-scale processes associated with groups of tasks

Considering Participant 1 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*. Similarly, *information seeking* appears to play a dominant mediating role in the tasks of Participant 2. This is characterised by medium 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 mix of tasks 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 presents a less complex pattern of activity. However, two concurrent cycles can be identified in the data. There is an information seeking/reporting cycle (period circa 3 hours, magnitude 10-20 minutes per hour). This is significant as it directly links the macro-scale process while highlighting the distinct characteristics of the embedded meso-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 focus on completing the main drawing, with other smaller tasks postponed by the participant. Although this case is significantly different in character from the other participants it still shares the critical features identified throughout this work.

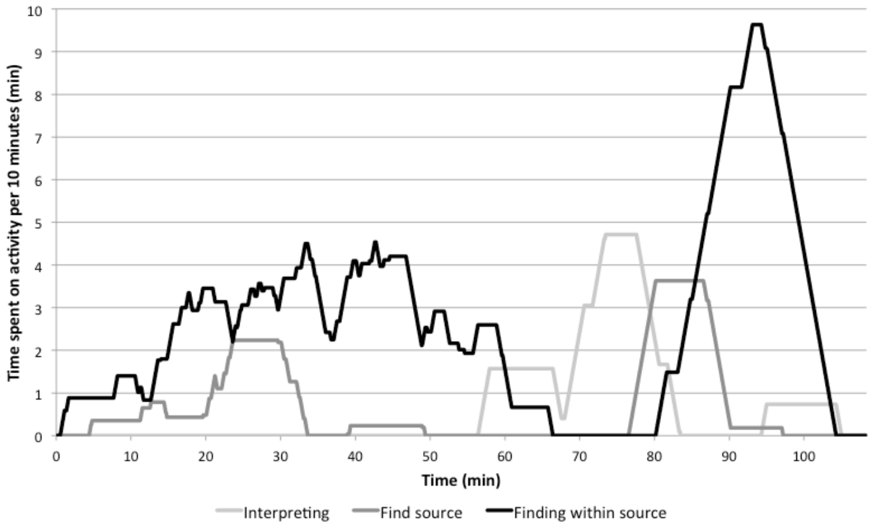
Concluding this part of the analysis the meso-scale results support the two important features identified in the macro-scale analysis. First, although the processes at the different scales are embedded they are distinct in their character. Further, although the activities associated with the macro-scale analysis could be linked to large scale design process descriptions, the processes evident at the meso-scale more readily link to models, such as, 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 associated processes there is significant interrelation between scales.

3.4 Micro-scale Processes

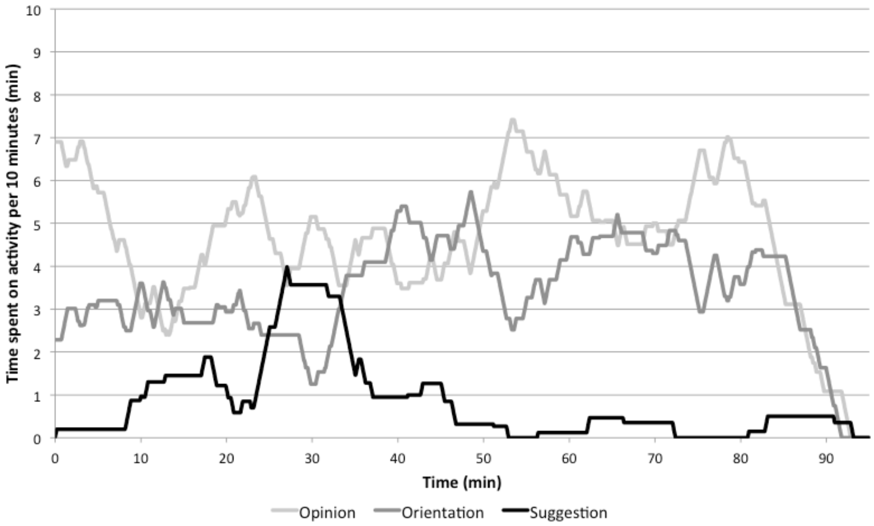
At the micro-scale, tasks are further decomposed into sequential groups of actions (Section 1.1). This makes this scale the most comprehensively described both in a general theoretical sense and in terms of design activity e.g. problem solution iteration (Dorst & Cross, 2001). Further, it also means that the progression of actions is highly task specific. As such, coherence of the proposed approach at this scale both reinforces the results from the macro and meso-scale analyses, as well as confirming the verisimilitude of the Activity Theory. This is achieved by examining a number of individual tasks due to the task specific nature of the actions considered at this scale.

Here, the participants' behaviour can be described as a number of actions occurring in series, which are embedded within the meso-scale task processes. It is these actions that form the foundation for the meso and macro levels. As an example of this sequential progression of actions, Figure 6a details an information task undertaken by Participant 1. Here, this can be linked to both organisational information processing theory (Hult et al., 2004) at the macro-scale or, further decomposed and related to cognitive information processing (Simon, 1978) at the lowest level. This further links to the work of Robinson (2010) which explores the impact of information seeking at the meso-scale.

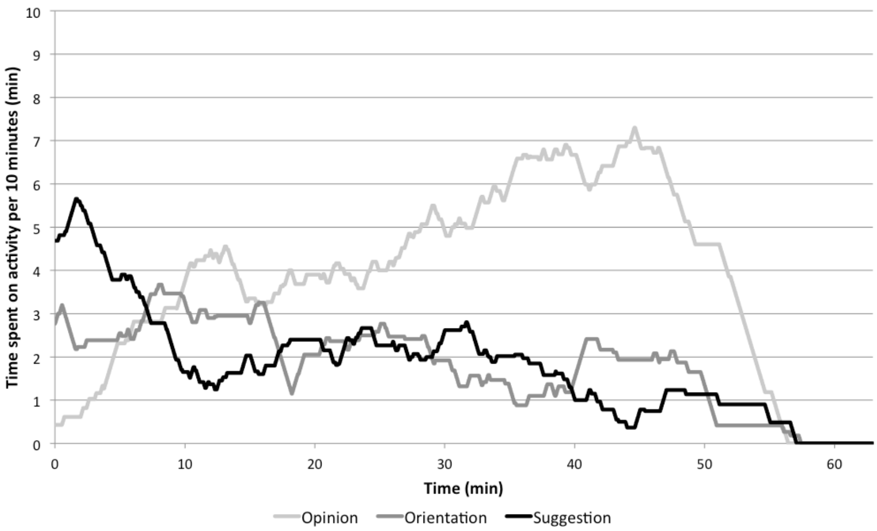
Finally, Figure 6b details the analysis of a design review conversation at the action level, focusing on the exchange of opinion. Here, the results support the previous multi-scale conception of design activity. In particular, the analysis highlights the micro-scale cycles of communication exchange that, although driven by the meso-scale task goal, 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 task – in this case ideation. Comparing these two examples reveals similarities in the interplay between the exchanges of opinion at the micro-scale despite being embedded within distinctly different tasks.



6a: Information actions 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 15-16)

Figure 6: Examples of micro-scale processes associated with groups of actions

3.5 Multi-Scale Embedded Processes

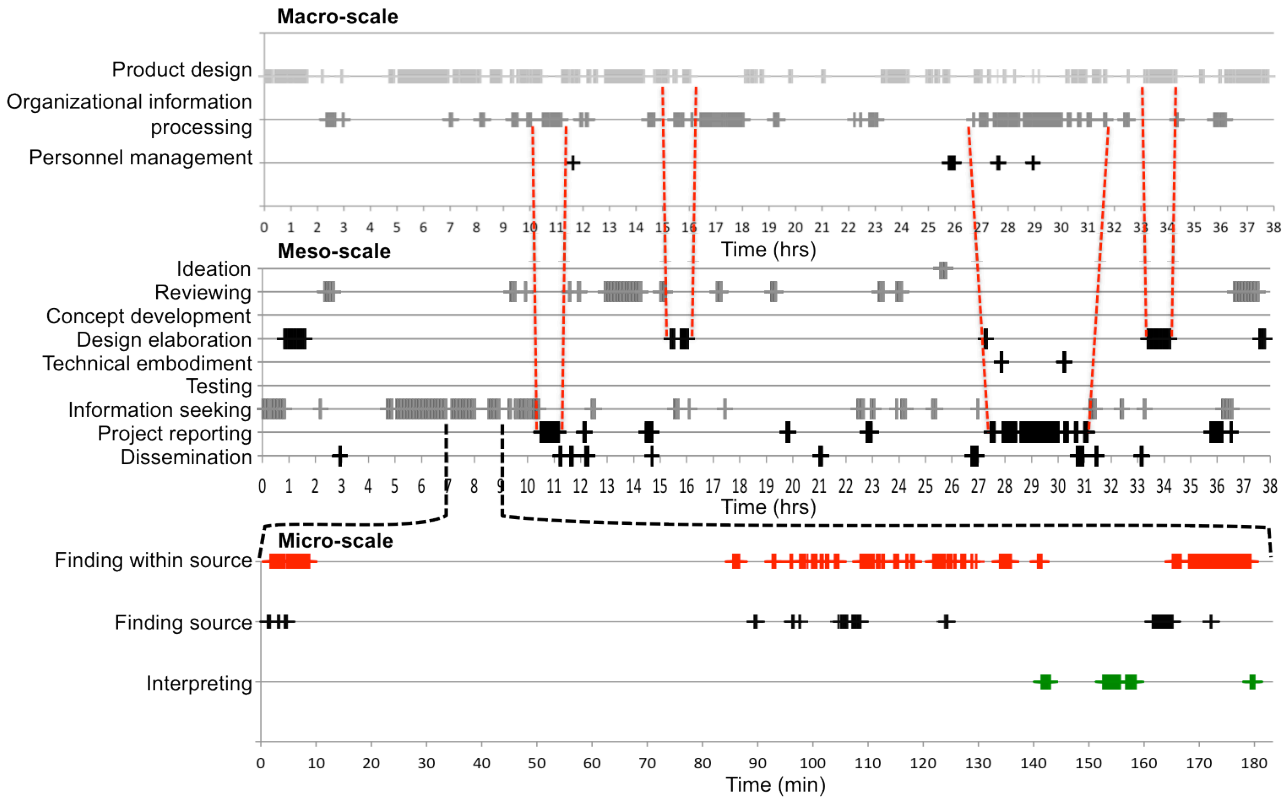
As previously stated this paper addresses two aspects of multi-scale analysis and the interrelationship between the scales. In the case of the latter we consider the embeddedness of processes across scales. Here, Participant 1's activity could be primarily associated with two parallel macro-scale processes – organisational information processing and design work. Decomposing these further through the embedded meso-scale processes reveals a number of additional features. Here, there are a number of different information cycles found in the data at the meso-scale. The first being a cycle associated directly with the development and communication of the design, 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, which was associated with design review activity. Finally, there were two periods of design elaboration that were directly linked to the macro-scale process i.e. the task level and activity level were aligned. This is characterised by the review (hours 12-14), and following design periods (hours 15-16, and 32-34). The dashed lines in Figure 7a denote these periods of direct linking between process scales. It is important to remember here that although other tasks are associated with the macro scale (as noted above) these are more embedded and implicitly associated.

With respect to Participant 2, fewer activities were identified that could be directly associated with macro-scale processes. In this case the only meso-scale cycle directly linked to the macro-scale information process was a reporting task (hours 35 and 37). This task was focused on 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 meso-level tasks seen in the study. Further, Participant 2 executed a wide range of different task types, with elements of concept design, and testing embedded in the wider process.

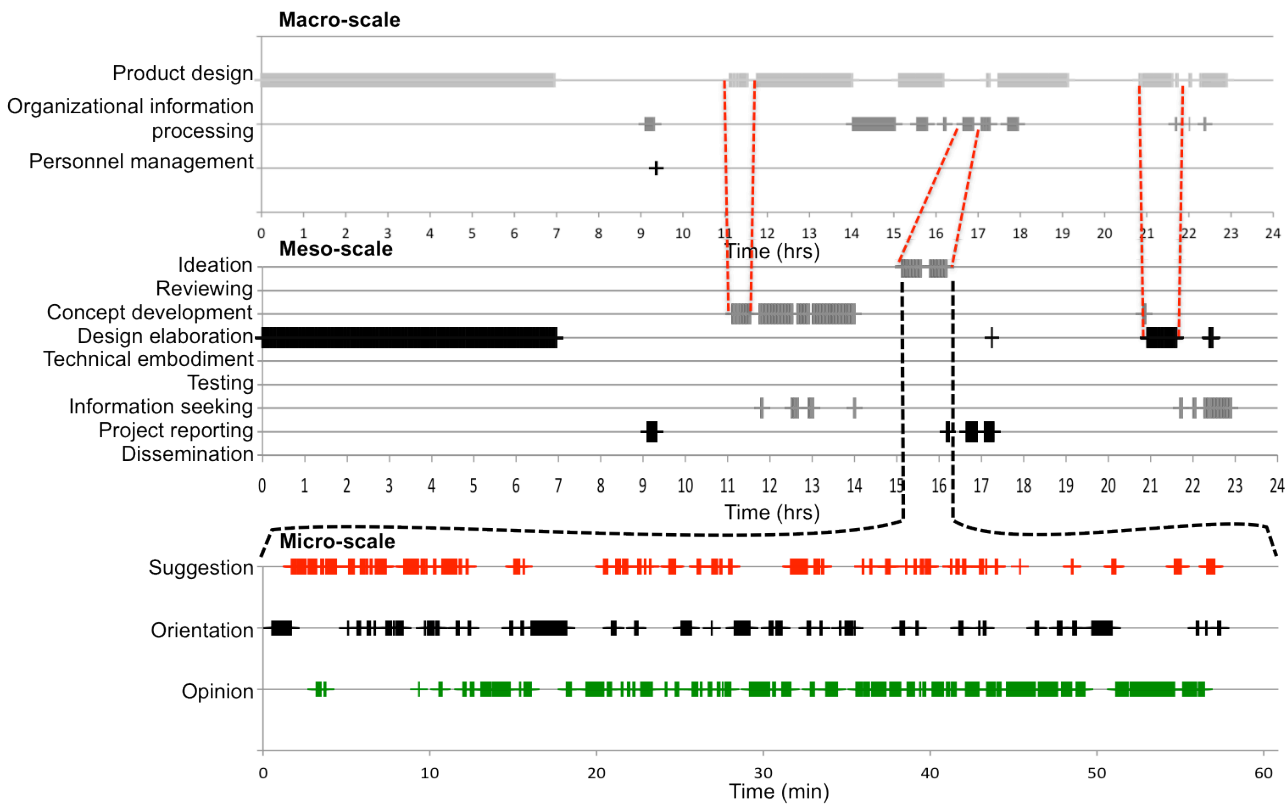
Lastly, Participant 3 displayed a more iterative cycle of design and concept development/ideation at the meso-scale associated with a focus on the product design process at the macro-scale. This contributed to the design process but little to the macro-scale information process, despite undertaking a number of specific information seeking tasks at the meso-scale. 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. These direct links between scales are again highlighted via dashed lines in Figure 7b. For example, the concept development task between hours 11 and 12 only contributed to the design process, with no linked tasks associated with dissemination or coordination (macro-scale organisation information activities).

This leads to a picture of design activity as a complex fabric of embedded 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 processes but do not dictate the nature of the meso-scale processes themselves. Further, although all the process scales are embedded some tasks can be more directly linked to specific macro-scale processes than the general body of work. This is further illustrated by the decomposition of the meso-scale to reveal yet more action cycles at the micro-scale. Here again, the action cycles present in the dataset are driven by and drive the progression of the meso-scale task processes but can be described independently. As this micro-scale is task specific Figure 7 illustrates two examples of the multi-scale conception of design work found in this study. Specifically, Figure 7a shows the cross-scale progression for Participant 1 with an example of the information seeking micro-scale process highlighted in Section 3.4. Here, both information seeking and reporting tasks are heavily represented as embedded within the macro-scale product design process. Further, decomposing one of these tasks shows how it is made up of a number of micro-scale action processes including finding and interpreting specific information. Similarly, Figure 7b illustrates the progression for Participant 3 with an example of communication focused micro-scale process.

Considering these different process scales both individually and collectively reveals a number of important implications for design research, which are explored in the next section.



7a: Embedded multi-scale processes with direct and indirect links for Participant 1



7b: Embedded multi-scale processes with direct and indirect links for Participant 3

Figure 7: Examples of multi-scale process representations

4 Implications and limitations

This section outlines the major implications, and limitations of this work, and revisits the driving question for this paper: *At what scales do distinct design activities and tasks exist and how are the various scales related?*

4.1 Implications: Multi-Scale Design Activity

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

First, the analysis explores the embedded multi-scale nature of the processes constituting design work. This is the first multi-scalar analysis of design work, and highlights the relationships between process scales. In particular this emphasises the need to consider other activity levels (Activity – Task – Action) when researching design work in order to better understand the possible implications from research across scales. However, describing this theoretically is still a significant challenge, particularly given the lack of uptake of Activity Theory in the design field. Although previous authors have described individual processes as drivers of design work, this analysis shows that design can be described as a number of scales embedded within one another. Further, these scales have significant impact on one-another, 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 tasks from all aspects of design work represented at the meso-scale. As such, it is perhaps more fitting to describe a stage with respect to a distribution of tasks 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 embedded, parallel processes suggests substantial further work is required across scales if a unified theory of design is to be adequately described. Although this is not the focus of this work – this conclusion has significant implications for the development of holistic design theory, such as, C-K (Hatchuel & Weil, 2003). 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. For example, the multi-scale processes described here suggest that C-K would need to be combined with other models at different levels of activity in order to fully explain and predict design behaviour in detail. This multi-scale nature of design and the interrelationships are depicted in Figure 8, which builds on the research framework developed from Activity Theory and described in Section 1.1. In this context, Activity Theory provides a framework for describing design work in a structured way – allowing for the development of predictive theory via the consistent combination of data from different scales and across multiple linked processes (Galle, 2008).

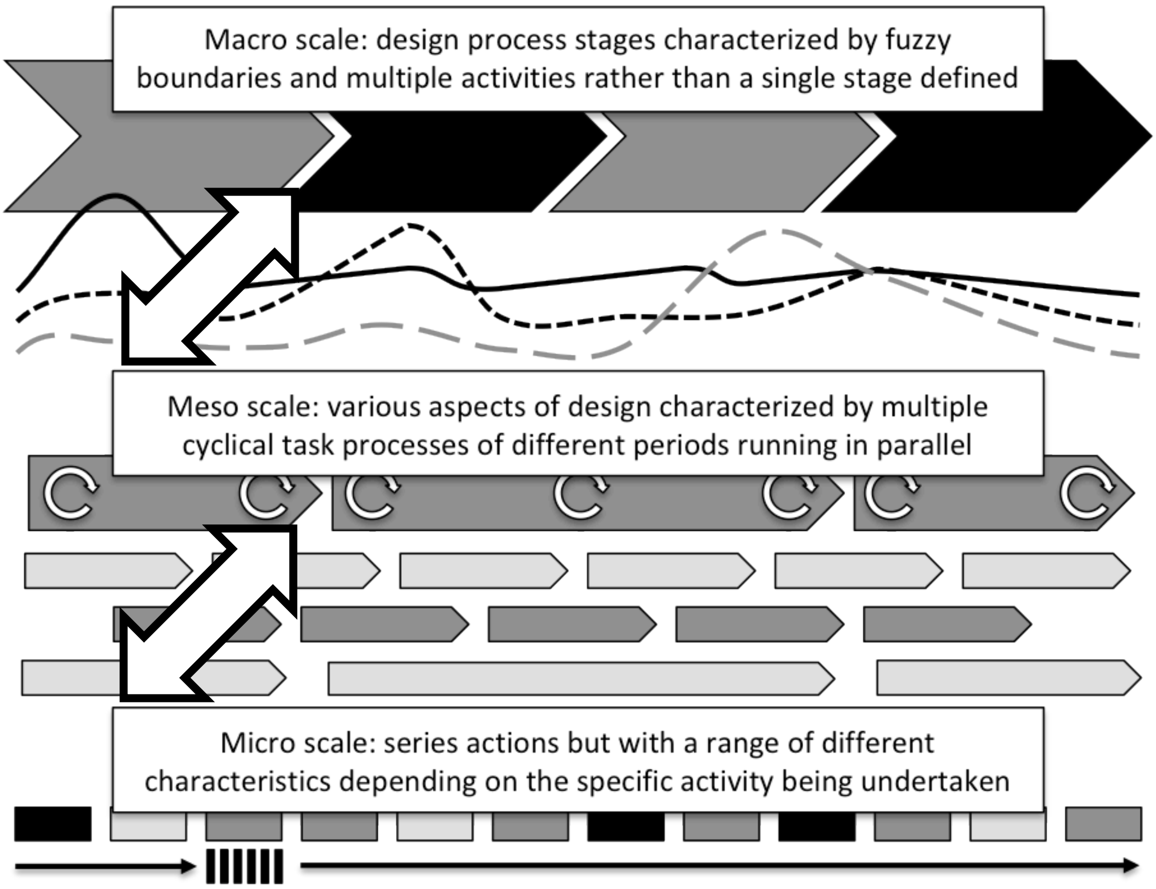


Figure 8: Reflecting on the multi-scale framework for describing design activity

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 relationships between the various processes – implying different types of appropriate intervention.

Second, design process models hide the fact that all types of design task 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 tasks and deployed on a weighted bases. This also highlights the need for further work on aspects of design 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.

Second, the study is limited by 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. As a qualitative validation, the results were presented back to the company and the participants. In this context, the participants felt that the activity descriptions were accurate with regard to their job roles and other responsibilities.

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 method used can be summarised as:

- Observe designer activity using a number of overlapping capture sources as well as contextualising the wider situation.
- Code and analyse the data at each scale (macro, meso, and micro) in order to identify processes scales.
- Consider cross-scale analysis in order to trace the relationships between the embedded processes.

The reported study built on the assumption that Activity Theory could be used as a new perspective for describing design work as parallel embedded activities across distinct scales. To explore this proposition the conceptual framework of Activity Theory was adapted to describe design work (activities, tasks, and actions) and provide a coherent structure for coding of design work at different scales. The developed framework and coding scheme was applied to a protocol study of three designers over a period of 1 month each. The proposed approach provided a substantially different insight into the study data than previous mono-scalar approaches. In particular, it offered significant new insight into the distinct scales and the interplay between the various processes involved in design work – something not previously described in the literature. Here design work was found to align with no single process but instead constitute a number of embedded processes, which can be considered to occur over three scales: micro-, meso- and macro-. Further, these processes were found to have embedded relations across scales. 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. Although significant further work is required in order to explicitly define the full extent of these relationships the need to consider multiple scales in design studies is clear

Although there are a number of limitations associated with this work the findings presented here hold significant implications and potential for both pure design researchers, and those seeking to support design in practice. In particular, the findings of this study present some important implications for the development of design theory and 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 tasks highlights the fact that all aspects of design are represented across the design process stages and thus have 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 linking to, for example, organisational information processing, design, and decision-making. There is also scope for expanding the link between micro-scale design actions and macro-scale manifestations of its affect in the wider design process.

Finally, we conclude by asserting that the ability to describe activity across scales affords 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.

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