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Title: Factors influencing communication in collaborative design

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Abstract:

Communication between people is commonly thought to play a major role in determining the success or failure of collaborative design projects. We conducted eight weeks of observation and 62 interviews in three design companies. Our findings indicate that communication is blamed for causing many problems which are not of an obviously technical nature. However, such problems are more often symptomatic of underlying factors related to information, representation, individual, team, and organisational issues. Examples of factors influencing communication at interfaces are people's understanding of the 'sequence of tasks' or 'goals and objectives' in the design process. With a system-theory informed conceptualisation of communication, we propose that awareness of such factors could assist design practitioners in targeting interventions and researchers in generating hypotheses about communication and design performance.

Keywords:

Collaborative design, communication, design management, teamwork, engineering design

1. Introduction

The development of all but the 'simplest' product requires experts from different fields to work with each other and with suppliers and users. During any product development process, problems can occur. It seems that insufficient or inadequate communication is often blamed for causing problems, in particular, if such problems appear as non-technical issues. Design engineers find it difficult to ascertain whether a communication issue is the cause of the problem or whether it is a manifestation of other aspects of the design process not working as well as they should. Communication is at the heart of collaboration between relevant stakeholders, however not all problems that are perceived as communication problems are caused by communication. To resolve such problems, design engineers and engineering managers in this situation need to untangle underlying issues. Many problems are multicausal, with some factors starting a chain of unfortunate events and other factors not stopping them or even aggravating them. Many factors may be out of the control of individuals, however understanding the factors helps to identify those that can be influenced. The aim of the paper is to encourage (design) engineers and managers to think broadly about the causes of perceived communication problems and to identify and draw attention to the factors that are within their own control and can thus be changed. This paper discusses 25 factors influencing engineering communication, derived from 62 interviews in three case companies, system-theory informed, and based on a detailed literature study. While the factors have been researched in isolation before, our contribution is to combine these factors to enable design engineers to reflect on their technical communication in a broader way than is currently done and to give design engineers and managers the opportunity to address factors under their control. As such, the paper offers a novel theory informed perspective on communication different than typically provided in engineering design and product development literature.

Designing is fundamentally a social process (e.g. Bucciarelli, 1994) involving collaboration of multiple stakeholders, e.g. at multiple team- and departmental interfaces. Collaboration connotes a more durable and pervasive relationship than a brief cooperation, involving commitment to a common mission and goals (Mattessich and Monsey, 1992). By extension and drawing on the definition provided by Kleinsmann et al., (2007: 60), collaborative design is understood as *"the process in which actors from different disciplines share their knowledge about both the design process and the design content"*. The authors continue to write that stakeholders "*aim to create shared understanding on both aspects* [the design process and the design content, incl. authors]*, to be able to integrate and explore their knowledge and to achieve the larger common objective: the new product to be designed."* Effective communication to coordinate work between design engineers and various stakeholders within and outside a company has often been mentioned as the main determinant of successful collaborative design (e.g. Minneman, 1991; Perry and Sanderson, 1998; Badke-Schaub and Frankenberger, 1999; Hales, 2000; Eckert and Stacey, 2001; Tenopir and King, 2004; Eckert et al., 2005) and product development as a whole (e.g. Allen, 1977; Clark and Fujimoto, 1991; Moenaert et al., 2000; Sosa et al., 2002; Sosa, 2008)..

The research reported in this paper was carried out as part of a wider study addressing the role of communication in engineering design. This included the development of a maturity grid tool to assess and guide communication in engineering companies (see [omitted for review]. Factors elicited and discussed in the study presented here are used in the maturity grids to gather differences in perspectives between stakeholders. In this paper, as a distinct and novel contribution, we propose to unpack what factors influence communication at team- and departmental interfaces within design organisations. There are communication problems on a personal level such as culturally and linguistically driven misunderstandings or plain dislike. In this paper we exclude such issues and point to literature on organisational communication (see Blundel and Ippolito, 2008). We observed that such personal factors become particularly pertinent as causes of conflicts in a designing organisation, when the underlying structural factors discussed in this paper are not addressed (Nelson and Campbell, 2012).

Before going into detail, the motivation for an analysis of the factors that influence communication itself is illustrated with two examples from industrial practice and literature from collaborative design in Section 2, which describe how factors work together to create a communication problem. This section also includes the theoretical frame for the conceptualisation of communication adopted and adapted here. Section 3 describes the research methods for acquiring and analysing interview data and presents an integrated framework for factors affecting communication. Section 4 investigates the factors that influence communication at team- and departmental interfaces so that actions for improvement can be taken, argues that communication is often wrongly blamed, discusses intervention possibilities for engineers- and engineering managers, and illustrates potential connections among the factors. The factors presented here are both levers for improvement and means to navigate and prevent communication problems. We also discuss implications for design practice, design research, and design education in Section 5 before drawing conclusions in Section 6.

2. Background

2.1 Examples of communication issues in industry

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The following examples illustrate how multifaceted a situation can be. In both cases the engineers complained that communication was not working well in their organisation, but saw only after our diagnosis that causes lay elsewhere. Examples are drawn from the interview-study described in the method section below.

Engineering designers and production engineers with different goals: A second tier aerospace supplier, having just gone through a change of ownership, followed by re-organisation and redundancies, was looking to expand its business by encouraging designers to engage in 'blue-sky' R&D as special innovation projects. The making of prototypes as 'demonstrators' as part of 'special projects' needed to be slotted into regular production. The design engineers and the production engineers were collocated, but both viewed the other group as unwilling to communicate and would, therefore, not make an active attempt to 'sort things out'. This led to a polite standoff. Both groups were working to fulfil their own performance metrics to avoid further redundancies, which gave them little space to 'help each other out'. All this within the context of the post 9/11 nose-dive in the aerospace industry, which was still felt at the time when the case study took place. With lack of profit, the company would face further redundancies and the employees were concerned that if they did not meet their targets their jobs would be on the line. Production was assessed by how effectively they managed to get the components through the factory and were therefore reluctant to be interrupted. Meanwhile, Engineering was assessed by the innovation activities that they carried out as part of special projects, which could lead to new business opportunities. The conflicting goals and objectives set for both parties manifested themselves as a communication problem, as depicted in Fig. 1.

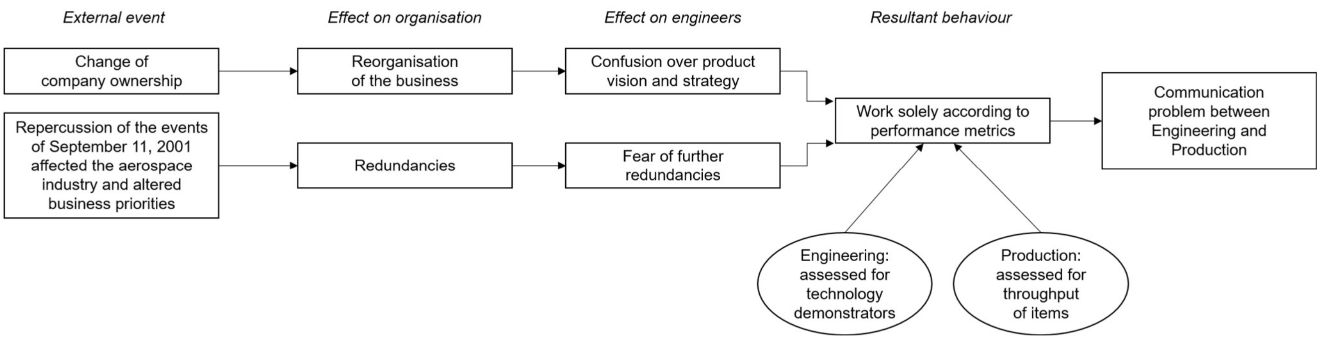

Fig. 1 Communication problem between Engineering and Production

Unclear processes around the order of spare parts: Top management at a small engineering tool manufacturer reported their frustration that the heads of the Service Support and the Production departments would not communicate with each other as much as the job required; and when they did then often only by carbon copying on email the whole management team or by having heated arguments. This affected collaboration in that the relevant stakeholders would principally prefer to avoid each other. The two departments were given conflicting targets. Production was to minimise stock and to use as many spares as possible, while the Service Support department was to respond as quickly as possible to customer needs and repair or replace parts on already sold machines. Performance assessment and salary bonuses were based on the degree to which the different targets were met.

What compounded the issue was the lack of a clear process for what should happen in case of a large order of spares that would have a financial outcome for the company almost comparable to the placement of an order for a new machine (what the company termed the 'works order process'). It was unclear as to whether such an order should be treated like a customer order for a new machine for which there were clear internal procedures involving all departments or whether such an order was to be dealt with solely by the Service Support and Production departments. A 'works order process' was not documented in any procedure for ordering spare parts. It usually ended up with the head of Service Support whose department needed the spare parts having to go to the head of Production to ask for a favour. As a consequence, both department heads got 'fed-up' with each other and concluded that the cause for their problems was down to communication (Fig. 2).

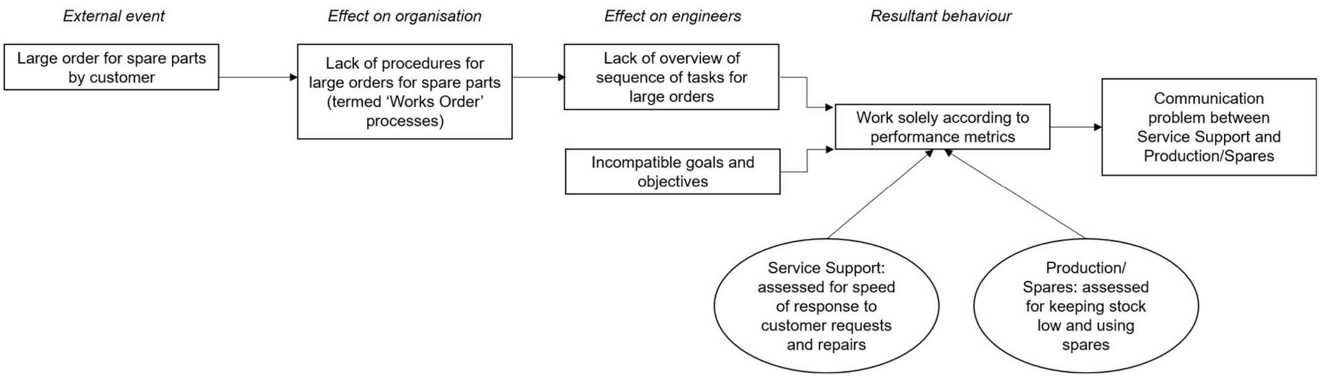

Fig. 2 Communication problem between Service Support and Production/Spares

These industry examples show us that there is an industrial need for digging deeper into what factors might be contributing to the above-mentioned situations. Before we continue with our own interview-study, we will first look for answers in the literature for a theoretical conceptualisation of communication and empirical studies of communication in collaborative design.

2.2 Perspectives on the research: Conceptualisation of communication

Communication is often characterised in terms of information transmission, based on the works of Shannon (1948) and Shannon and Weaver (1949), who describe communication in terms the transmission of messages from an information source which generates the message, a transmitter that encodes the message into signals, a channel that transmits the signal, a receiver that decodes the message from the signal, and a destination where the message arrives. This model has originally been devised to describe noise reduction in electric data transmission and has now been widely applied to human communication. Another view on communication comes from the philosophy of language, which is concerned with shared understanding of the meaning of words, e.g. as Wittgenstein (1953) points out meaning is often fluid and negotiated in a group and thus impenetrable to outsiders, while some words like facts or proper names are more likely to be understood in the same way by all Kripke (1982). This account points to the social nature of communication without explaining the wider social system. We consider design as a social system (e.g. Bucciarelli 1984; 1994) and communication as being a constitutive part of such a social system (e.g. Luhmann (1984; 1992; 1995); Craig (1999); Krippendorff (1971)). The perspective of system generation through communication is most strongly articulated in works by the sociologist Luhmann (1995) – who builds on a number of intellectual traditions with a broader perspective, in particular including Shannon's information theory (1948), Bühler's speech theory (1934), and Maturana and Varela's (1975) research on self-organising systems to name a few. (For an overview of communication theories in the context of design, see Maier et al., 2005 or Crilly et al., 2008).

Luhmann (1984; 1992; 1995) conceives of communication as a combination of three aspects: **information, utterance,** and **understanding**. Communicators have to: choose the information they would like to transmit out of many other possibilities, decide upon an adequate way of transmitting the message, and the communicator at the receiving end selects an appropriate way of interpreting and understanding the message. Understanding does not necessarily imply agreement. An utterance containing a particular piece of information might be produced by one communicator but understanding occurs in another. A central point in Luhmann's concept of communication is that the three selections (information, utterance and understanding) form an insoluble unit and only as a unit do they constitute communication. As a result, communication constitutes an emergent property of the interaction between many (at least two) individuals. It is characterised in this view as coordination of behaviour. A number of factors influence this coordination of behaviour in an organisational context such as the perception and expectations of ones roles and responsibilities, hierarchies, goals and objectives. In addition to being motivated by an industrial need (Section 2.1), this is another reason for why we are focusing on influences on design communication in industrial practice.

When conducting and analysing our empirical observation- and interview-based data and selecting the factors presented in this paper, we adopted Luhmann's categorisation of information, utterance/interaction, and understanding/situation. These informational, interactional, and situational aspects are complementary and cannot be viewed in isolation. Considering all three aspects when analysing communication is important as conceptualisation influences action. What one focuses on often impacts the improvement measures and solutions one may or may not develop (Clancey, 1997). For example, if one were to think of communication problems as a function of lack of information, one would most likely try and find a solution that increases the chance for obtaining information.

Taking a system-theoretic perspective emphasises communication as an on-going process rather than the result of discrete communication episodes. In this perspective, communication is successful when it continues. Continuation may encompass acceptance and rejection of an argument as rejection of an argument does not mean the end of a conversation but asks for further communications (Willke, 1989:106; Seidl and Becker, 2006). This is particularly relevant to engineering practice as it is important to continue communication between designers, to know what the other expects and what the boundaries of understanding are. This is a perspective that has to-date not been explicitly articulated in literature on communication in design. However, it resonates with Hales (1993) referring to notes that are used throughout the design process and can form the basis for continuing conversations in the future or McDonnell (2012:45) who examined conversational strategies to keep the flow of collaboration and to progress the design. In a similar vein, rather than solely focusing on the identification of failures and eradication of weaknesses, our work presented here therefore focuses on creating the conditions for follow-on communication.

2.3 Literature on communication in collaborative design

Although, many aspects of designing are undertaken by individuals on their own (e.g. Ericsson and Simon, 1993; Cross and Cross, 1996), designs are developed largely through social processes of argumentation and negotiation between participants (e.g. Bucciarelli, 1984; Minneman, 1991; Valkenburg and Dorst, 1998; Stempfle and Badke-Schaub, 2002). The literature on communication in collaborative design is rich, and we can only provide a flavour of the ongoing discussions to support the development of the set of factors proposed here.

Importantly, to-date, empirical studies have addressed communication in collaborative design mainly from two interconnected viewpoints: understanding what impacts the collaborative design process and addressing the role communication plays in the generation of the design object.

Understanding what impacts the design processes, barriers, enablers, and indicators for knowledge sharing have been studied in a number of industry sectors. For instance, recurrent motifs are antecedents, the nature, and consequences of team cognition and shared understanding, in the aerospace industry by, for example, Søndergaard et al. (2007) and in the automotive industry by, for example, Kleinsmann and Valkenburg (2008). We also find studies taking a broader view for structuring collaboration in general, e.g. Gendron et al. (2012) and studies presenting a taxonomy for the classification of collaborative design (e.g. Ostergaard and Summers, 2009). Empirical studies describing and analysing what impacts this collaborative design process and management of engineering design projects categorise influencing factors in a number of ways. Hales (1993) argues that design processes are affected by influences on the personal, the project, the corporate-, and microeconomic- and macroeconomic levels. Badke-Schaub and Frankenberger (1999) describe 'prerequisites' for managing critical situations in design projects pertinent to the individual- and the group level, boundary conditions, the level of task, the design process and design output. Whilst we get closer towards understanding what impacts collaborative design, in the studies selected above, communication is listed as one 'element' among many. Thus, to help industrial practitioners and researchers to improve communication, we need to look at what communication itself is influenced by, and therefore, we need to turn to the literature on empirical studies of specific design communication episodes in collaborative design.

Addressing the role communication plays in the generation of the design object, researchers have engaged in studying the fine details of human interaction (e.g. (Luck, 2013; McDonnell and Lloyd, 2014; Eris et al., 2014)), to uncover how through multimodal communication the design object emerges and to gain insight into how best to support (creative) collaboration. Focusing, for example, on the nature and effects of conversation by analysing excerpts of talk between an architect and a client, Oak (2011) argues the collaborative nature of conversation contributes to understandings and assessment of the design object. Employing latent semantic analysis, Dong (2005) examined designers' use of words to predict the level of shared knowledge construction in collaborative design. The studies selected above offer fine-grained and detailed descriptions of how design practice unfolds, by shining analytic light on the communicative micro-interactions in collaborative design situations.

In summary, to-date, the literature shows on the one hand a lack of studies explicitly stating their underlying conceptualisation of communication and on the other hand a disconnect between studies presenting detailed micro-level analyses of distinct communication episodes and macro-level studies concluding that communication is one crucial ‘element’ in a collaborative design process, without discussing what communication itself may be influenced by. This is not surprising as the studies were conducted for different purposes. By contrast, an actionable meso-level is missing of modifiable factors influencing design communication within design processes. This article suggests, therefore, a comprehensive theory informed and empirically driven set of factors influencing engineering design communication to enhance understanding of communication and to support improving specific situations.

3. Research methods and -perspective

Ethnographically informed fieldwork was carried out in three engineering companies in the UK. This entailed observations of design work and interviews. The first author spent from one to four weeks among design engineers in the respective companies which allowed for an understanding of the designers’ working culture and practices. Observation also yielded the illustrative examples in section 2.1. Interviews carried out during the observation period served to elicit factors influencing communication in design. The second author joined the interviews in the three case study companies to understand the company context. This enabled the authors to discuss the communication situations and interview quotes from different angles. This study complements other empirical work on design communication by the authors in automotive design (Maier et al., 2009; Eckert and Clarkson, 2004). While we did not use these studies explicitly in this paper, the factors identified also cover the communication situations studied there.

3.1 Eliciting factors influencing communication through semi-structured interviews

In total, 62 semi-structured interviews were conducted with design engineers and managers from three companies in the aerospace, engineering tools, and information technology sectors respectively. The engineers varied in seniority and experience. One company is an aerospace supplier with several thousand employees worldwide and several hundred employees for the business sector in question. The other company has several thousand employees worldwide and operates in the area of information technology. The third company is a small engineering tools manufacturer with fewer than hundred employees.

All interviews were conducted at the participants' place of everyday work. Each interview lasted maximum one and a half hours and followed the same format. We used a semi-structured approach and the same checklist of headings in each interview to prompt the discussion. This allowed consistency across the sample of people interviewed and did not impose a structure as to how an individual should respond but rather capture their personal experience and perception. The checklist headings included the engineers being asked to speak about their current position, followed by a description of the projects they were working on, the nature of interactions with other teams, and what the interactions were influenced by.

3.2 Empirically derived coding of interviews

Interviews were captured in field-notes and audio-records where allowed. Computer-aided qualitative data analysis software (QSR, 2006) was used to assist in filing and analysing the written and transcribed interview data. The method used to analyse the transcripts was inspired by a grounded-theory approach (Corbin and Strauss, 1998) and thematic content analysis (Krippendorff, 2004). This approach is used by other researchers with similar goals of identifying key themes and developing a framework of determinants of communication processes, e.g. in conversations among designers (Luck, 2003) or for describing moderating influences on the design as communication process between designers and consumers (Crilly et al., 2004).

Transcripts were coded by annotating pertinent issues through keywords/codes. Keywords were condensed into a list of more than 20 factors and subsequently grouped into five categories of influence. The process of coding the transcripts to elicit factors influencing communication in collaborative designing evolved as follows: The first author identified codes emerging from the material and assigned them to the appropriate sentences or paragraphs of the transcript. These initial very detailed codes were then merged and grouped in a tree structure, what Miles and Huberman (1994) call 'factoring', as the outcomes of this process are factors.

Coding unfolded in three rounds. To illustrate, an interviewee would explain the importance of timely and accurate availability of the 'bill of materials' or data on 'dimensions of a certain component', or 'procedures'. In the first round of coding these codes were listed individually. In the second round of

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coding the researcher assigned these comments to the code ‘availability of information about product specifications’ or ‘availability of information about procedures’. In the third and final round of coding, the factor was grouped under the category ‘information’ (see Fig. 3). In total, five theory informed categories were discerned: **information, representation, individual, team,** and **organisation**. Association of codes to categories was kept within the context of influence within which the engineers mentioned the factor. The categories and association of interview quotes with factors were discussed with the co-authors for inter-coder reliability before checking with the interviewees for ‘member validation’ of the findings and for credibility in the industrial context of origin (Bloor, 1997).

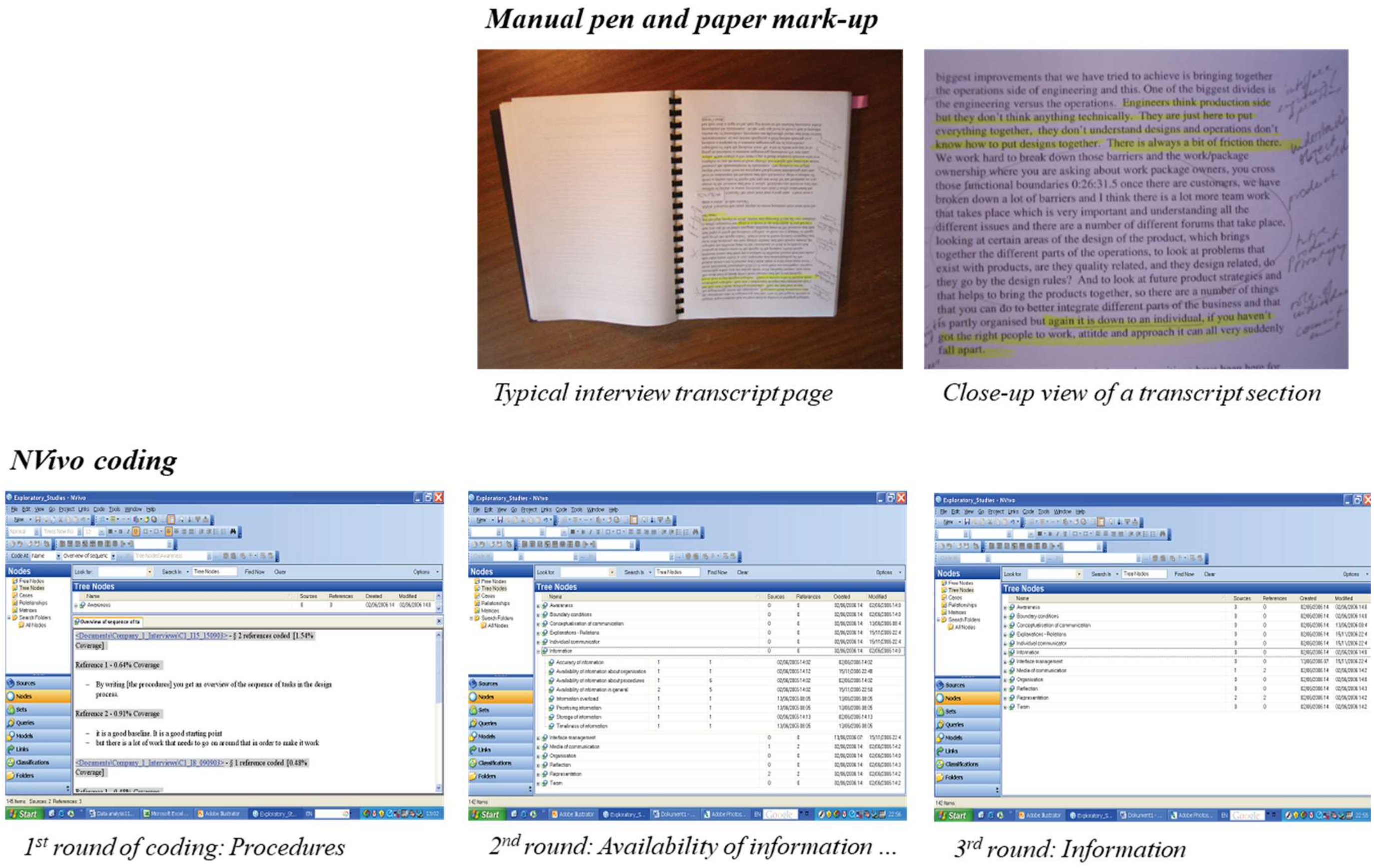

Fig. 3 Visual representation of interview coding process

In addition, yet outside the scope of this paper, we performed statistical explorations of correlations between factors and graph-theoretical analyses to detect direct and indirect linkages, cycles and clusters between the networks of several factors. The idea being that once we know how the factors are connected, an impulse at one point of the web of connections will have a ripple effect through directly and indirectly linked factors (for details and illustrations, see Hepperle et al., 2007; Maier et al., 2008:42). In order to make use of such relational knowledge and appropriately to devise interventions, this paper focuses on the respective factors.

3.3 Selection of influencing factors: most prominent in interview and possibility of intervening

Two main criteria were used in the process of arriving at the final set of 25 factors:

- **Frequency:** Most frequently mentioned factors were counted, and counting proceeded as follows: In order for the selection of factors not to be biased by the prevailing culture of the companies in the sample, we only counted factors that were mentioned in all three companies, at least by three interviewees, and occurred minimum ten times. Also, a factor mentioned several times by the same interviewee was only counted once, even if it occurred more than once throughout the interview. A quote from an interviewee can be associated with one or more codes.
- **Influenceability:** We focused on factors that can be influenced and altered by individual engineers and engineering managers – an argument also made in related research in innovation management (Hauschildt and Salomo, 1993; Ernst, 2002). Therefore, interpersonal factors have been excluded. For an overview and description of such factors see, for example, Crilly et al. (2004: 571). Studies on influences of personal characteristics on communicative events include, for example, considerations of age, gender, experience (e.g. Fischer et al., 2003), communication skills, emotions (Mann, 1999), and personality (e.g. Hackmann 1987; Vianen and Dreu, 2001). Communication may also largely be defined by language and cultural differences (e.g. Dahlin et al., 2005) and be affected by situational influences such as team composition (Belbin, 2003), the type of project (Belassi and Tukel, 1996), legislative changes, or global economic and financial market developments.

3.4. Theoretically informed framework for categorising factors influencing communication

A system theoretic perspective sees communication as a continuous process of communication leading to further communication and thereby bringing a social system into being; and in addition to generating a social system also maintaining it. However, practitioners described their experience with communication through discrete acts of communication, which included activities or events leading up the communication act, the communication act as such, and the consequences emanating from it. For example, the communication problem between engineering and production, illustrated in Figure 1, was seen as an ongoing problem consisting of a multitude of individual episodes, where production did not respond to engineering in the way engineering had wanted.

The integration offered in this paper combines this perspective of communication as discrete, episodic acts of communication with the perspective of communication as a process, where communication plays a vital role in generating and maintaining social systems. This allows analysing the systemic context of factors as a temporal sequence of factors feeding into communication and factors resulting from communication, as engineers might want to tackle both the cause and effects of perceived communication problems. To re-iterate, Luhmann characterises communication as an insoluble combination of three aspects (see Section 2.1): information, utterance and understanding, which has informed the categories of factors reported here. The aspect of information is kept as one category, and for the aspect of utterance, we limit ourselves to engineering-specific representations and exclude non-engineering specific forms of expression as they are often outside the control of engineering designers and managers. The aspect of understanding relates to the level of analysis in communication episodes, which we have broken down into the three embedded levels: the individual, the team and the organisation.

4. Factors influencing communication in design: levers for improvement

This section provides a comprehensive picture of the factors affecting engineering design communication. Association of codes to categories was kept within the context of influence within which the engineers mentioned the factor mapped following the conceptualisation of communication as an insoluble unit of information (informational influences), utterance (representational influences), and understanding (situational influences, including individual, team, organisation). The utility of this mapping is first the connection to theory which emphasises a systemic framing of communication where the area of intervention may be different from the area of impact and second to indicate that while everybody in an engineering company is potentially impacted, not everybody can affect all factors equally (see also Section 4.5). Communication can be affected on different levels in an organisation. While some factors are within the control or influence of individuals, others require a concerted effort from an organisation. Therefore, the perceived communication problem needs to be seen in a wider context.

Each factor is explained and supplementary references are provided, and each factor is a lever to improve communication or at least puts thinking about communication in engineering design in perspective. From the theoretically informed and empirically derived elicitation of factors, the authors would not want to presume an order of importance or priority. For an overview see Tables 1-3 over the next pages, including the number of times a factor was mentioned, key references and an illustrative code as quote from our interviews. A more detailed explanation of the factors is provided following the tables.

Table 1 Record of factors affecting communication:

Influences relating to information and representation

Level of influence	Factor	#*	Interview quotes	Literature references
INFORMATION	Availability of information about ... product specifications procedures company, and competitors	 43 39 33 33	*"[…] a lot of the time we know what we want to do, but there might not necessarily be the information that we need available at the time when we need it to be available." (I1, Aerospace supplier C1-I1)*	Court (1995) Aurisicchio (2013)
REPRESENTATION	Product representations	27	*"I was fed up people dripping broken hardware on my desk. You come back from lunch and you find this chunk of metal on your desk and it is broken with a phone number next to it." (C1-I4)*	Henderson (1999) Boujut and Blanco (2003) Wlazlak et al., (2019)
	Terminology	13	*"Big area of communication is not properly understanding what each of them [other departments] requires, what other engineering languages they [other departments] speak […]. There is a strange, how to put it, for example Sales and Marketing people work in a different world. How they describe things." (C1-I6)*	Bucciarelli (1988) Dougherty (1992) Vermaas and Eckert (2013) Meluso et al., (2020)

** Frequency of occurrence in interview*

4.1 Information – what is communicated

Engineers mentioned that many of the difficulties associated with completing design tasks relate to information – lack of data, wrong data, not-timely. Forty three out of 62 engineers pointed to the importance of availability of information. This was the most frequently mentioned issue, next to knowledge about the preferred type, format, and further processing of information.

Availability of information

Repeatedly, reference was made to problems stemming from lack or overload of information, information not being right, not arriving at the right time, and not arriving at the right place. Rectifying errors due to lack of information is a costly way to learn, yet it happens in most design processes. Designers' communication is affected by availability of information, specifically of product specifications, procedures, competitors' products and strategies, and availability of information about their own company.

Designers deal with a vast amount of information at every stage of the design process (Restrepo, 2004). Due to the inherent complexity of many design products and engineered systems, design engineers spend a significant amount of time searching for, prioritising and handling the information available (Aurisicchio, Bracewell and KM Wallace, 2013). Searching for information can take up considerable time and acting on incomplete or false information can lead to compromised decision-making. A team is able to make best use of its pooled knowledge (Court, 1995) by guaranteeing availability of information and sharing information between members according to their members' individual needs and preferences.

4.2 Representation – how is information represented

The engineering designers interviewed pointed to the ubiquity and variety of product representations and terminology used in interaction with their peers and other stakeholders.

Product representations

Here, the engineers referred in particular to physical pieces of hardware and lines of codes as being used to inform colleagues about their decisions as well as document the progress of the design process. For example, one interviewee referred to the fact that people kept leaving broken hardware on his desk (see Table 1 for quote). The physical piece of hardware was used by the engineer to elicit a response from his colleague. We also observed that engineers are using an increasing amount of mathematical models such as performance simulation models.

From literature we know that visual representations are fundamental to engineering design and form part of the visual culture of engineers (Henderson, 1999). Typically, design engineers interact with their designs through a whole spectrum of representations from Gantt charts, Bills of Materials, 'requirement lists' to 2D sketches, different types of drawings, 3D CAD models, and physical prototypes; *"[T]he lingua franca of engineers in the modern world"* (Ferguson, 2001). This requires understanding of the expressive properties that individual representations exhibit (Monö, 1997; Crilly et al., 2004; van Dijk and van der Lugt, 2013) and understanding the technical language (terminology) and drawing conventions (notation) used (Bucciarelli, 1988). The nature of different types of information necessitates different representations. A number of representations of the product, such as a drawing, a requirement list or a physical prototype serve visualisation purposes and are used to derive information (Eckert and Boujut, 2003). What form of representation is most appropriate depends on what is to be emphasised and what kind of participation is desired and the designer's choice how to communicate influences what is achieved in the end. Different product properties are expressed in different and often incommensurable ways, where no single representation can capture all aspects of a product or a process. Annotations may be used to clarify design rationale (Hisarciklilar and Boujut, 2009).

Terminology

Many design engineers interviewed were technical experts within the companies to which other project teams referred when they needed advice. Giving advice entailed translation of their knowledge and explanation of terminology to people with different disciplinary backgrounds.

Participants in the design process, be they mechanical engineers, electrical engineers, machinists, marketing managers all engage in their specific 'object worlds' which are worlds of technical specialisations, characterised by specific dialects, systems of symbols, and metaphors (Bucciarelli, 1988: 162). Specific terminology, such as part names can be company specific and the same word might be used for different issues or parts. Engineers may use different notions of seemingly generic yet abstract terms, such as 'functions' (Vermaas and Eckert, 2013) or 'parameters' (Meluso, Austin-Breneman and Uribe, 2020). Differences about engineering terminology might lead to miscommunication which in turn has been shown to affect performance (Meluso, Austin-Breneman and Uribe, 2020).

4.3 Understanding – individual level of influence

Successful communication between designers is influenced by a variety of factors which could be positioned on the level of the individual communicator. The following factors have been identified and listed Table 2, together with corresponding interview quotes and references in literature: Knowledge of information needs, use of capabilities, education and training, overview of sequences of tasks in the design process, and autonomy of task execution. Interestingly, personal factors such as how friendly or co-operative a colleague is was not often mentioned in interview. However, when these factors were mentioned, they were excluded for reasons stated in the introduction. Another reason may have been that engineers interact with a large number of individuals.

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Table 2 Record of factors affecting communication: Influences relating to the individual level.

Level of influence	Factor	#*	Interview quotes	Literature references
INDIVIDUAL 	**Knowledge of information needs**	8	*"I think there are two aspects to my work (…). One aspect is all about communication - obtaining and giving information. The other is essentially about non-communication: figuring out a problem by concentrated, isolated study – though that can break out into communication if it's the kind of problem to involve others. In both cases, I want to know what information is available and required." (C2-I4)*	Hicks et al. (2002) Wallace et al. (2004)
	Use of capabilities	14	*"Engineers don´t work here because they get hugely paid well. The salaries are not too bad but they work here because they find the work interesting. It´s satisfying making things fly and more interesting than designing a mobile phone, although there is interesting engineering in that. They like working in the industry, so most of them are here for a long time." (C1-I11)*	West (1996) Houkes (2001)
	Education and training	12	*"The engineers even though they may not be doing […] they are not doing a disaster recovery paper chasing they still come in frequently to ask where they would find something or expecting us to know their processes." (C1-I16)*	Eckerson (1990) Wallmeier et al. (2000)
	Overview of sequence of tasks in the design process	38	*"Critical aspect in the design process here is possibly that there isn't really a formal layout of what we do. There is a project plan but I mean for the actual design process itself. There are normally a set of steps you have to do before you move on to the next level. There is not really anything in place here, it is word of mouth. Checking with the people you are going in the right direction, doing the right thing." (C1-I3)*	Dourish (1992) Flanagan et al. (2007)
	Autonomy of task execution	12	*"I need to be able to execute my own tasks." (C2-I21)*	Van Vijfeijken (2002) Gratton and Erickson (2007)

** Frequency of occurrence in interview*

Knowledge of information needs

Pointed out in interview, while availability of information is an information retrieval process from the point of view of the beneficiary, for effective communication it is important to know what pieces of information others require. Some of the key challenges for individual engineers are understanding their own information needs and providing others with what they might need.

In order to know what information is needed, engineers need to make their assumptions and personal preferences known (Rentsch, Heffner and Duffy, 1994), have adequate question-asking strategies (Eris, 2002), be sufficiently aware of the sources and type of information (Leckie et al., 1996; Heisig et al., 2014), and have an overview of the design process, to anticipate the information needs of their colleagues (Flanagan, Eckert and Clarkson, 2007). Overall, knowledge and information needs in design and product development have been studied from different angles, with main concerns centred on knowledge capture and experience (Marsh, 1997), the reuse of information (for a review see also Heisig et al., 2010), and the nature of knowledge and information needs of engineers and designers (Hicks et al., 2002; Wallace et al., 2004; Court et al., 1996; Kuffner and Ullman, 1991; Wasiak et al., 2010).

Overview and awareness of sequence of tasks in the design process

A general overview and awareness of the 'sequence of tasks in the design process' was the second most frequently mentioned factors (38 engineers, see Table 2) to assure successful communication and a successful design process.

Awareness of the work of others facilitates communication and is therefore a basis for engaging in any kind of collaborative activity (Moody, 2000). Awareness and communication are related as lack of awareness can cause communications to diminish and communication can lead to awareness. Overview and understanding of others' activities and the sequence of tasks in the design process enables one to understand the context for one's own activities, goals and motives (Dourish and Belotti, 1992; Schmidt, 2002; Flanagan et al., 2007).

Use of capabilities

The engineers interviewed and observed seemed highly motivated and committed to the projects they were working on and often worked to finish the task they were pursuing, no matter how long it took. They attributed their commitment and motivation to the application of their 'technical skills and use of their capabilities' to contribute to a successful end product. They were enthusiastic about the problems they addressed and eager to continue being provided with a licence to experiment with alternative and innovative solutions to a problem. Especially at the information technology company, most staff had written their own problem-specific software tools, which the group used to fulfil specific tasks.

Freedom to pursue innovative ideas (West and Altink, 1996) and opportunities to make best use of individual capabilities (Houkes and Janssen, 2001) motivates engineers to seek and share information, discuss concepts and solutions and thus influence communication.

Autonomy of task execution

The engineers stated that they need sufficient time and latitude to carry out their tasks autonomously whilst collaborating with others. Interestingly, interviewees often mentioned this in connection with knowledge about their and their colleagues' roles and responsibilities. Importantly, we observed that the more designers were given the opportunity to work autonomously on some tasks, the more they voluntarily shared information when results were achieved and co-ordinated their work with their colleagues. Designers felt that the pressure to cooperate was gone when priority was given to solving the technical task.

From literature we learn that communication improves when the roles of the individual team members are defined yet team members are given freedom in how to achieve their individual tasks (van Vijfeijken et al., 2002; Gratton and Erickson, 2007).

Education and training

To keep abreast with new technological developments, to build and maintain their capabilities and to deepen expertise, the engineers interviewed mentioned that education or training is an important factor that influences the way they communicate with their peers. Knowing someone's training helps identifying the right person for information.

Education and training of engineers has the potential to facilitate learning and thus potentially reflection (Wallmeier *et al.*, 2000), and receiving training is seen as a source of motivation for the team members (Eckerson, 1990).

4.4 Understanding – Team level of influence

Design engineers interviewed pointed towards a 'supportive environment' as affecting the way they communicate and perform their daily design tasks. The term relates to the atmosphere created within a project team, influenced by the wider organisational culture. A number of factors were given as contributing to a supportive environment: 'collaboration', 'common goals and objectives', 'team identity', and materialisations of team reflections, e.g. 'best practices', 'lessons learned', and 'project reviews', see also Table 3.

Table 3 Record of factors affecting communication: Influences relating to the team level.

Level of influence	Factor	#*	Interview quotes	Literature references
TEAM 	**Collaboration**	**17**	*"[...] now it is more individual tasks and people tend to be individuals as supposed to work collectively and I think that is a bad thing for communication flow" (C1-I17)*	Trist (1977) Pinto (1993)
	Common goals and objectives	**16**	*"It is quite difficult because of the sort of drivers in the area, we got the operations area, they are sort of focused on we must get all this hardware, the units completed and out of the door, oh, you want to talk about new designs, but I want to get this done by the end of the day and don´t want to talk about the new design." (C1-I12)*	Raia (1974) Kleinsmann and Valkenburg (2008)
	Team identity	**11**	*"I think they have to try and get the team spirit back. If they can see things are working more collectively then they will want to put more in collectively as opposed to as I said earlier leaving it and hoping someone else would do it." (C1-I17)*	Tajfel (1982) Macmillan (2001)
	Design reviews	**17**		Ayas (1997) Klein (2003)
	Lessons learned	**18**	*"I think it is critical for communication to try and learn from what you have done before." (C1-I7)*	Dörner (1996) Badke-Schaub et al. (1999b)
	Best practice	**11**		Reymen and Hammer (2002) Valkenburg and Dorst (2008)

** Frequency of occurrence in interview*

Collaboration – regularity and effort to improve collaboration

Regularity and willingness to collaborate was predominantly referred to in conjunction with existence and synchronised execution of 'common goals and objectives' and 'information sharing'.

Collaboration can be conceptualised as the degree, extent and nature of working together and the mutual help between project team members (Trist, 1977; Pinto et al., 1993:1286; Brown and Eisenhardt, 1995). Collaboration has been shown to promote productivity by helping individuals perform more effectively (Laughlin, 1978).

Common goals and objectives

As the introductory examples showed (Section 2.1), when teams have conflicting goals, people avoided contact which in turn tends to manifest in a lack of communication. Adversely, as design engineers interact with multiple company-internal and –external stakeholders, interview results show that engineers' expend a lot of energy attempting to orient toward multiple and often conflicting goals, in an effort to satisfy those rather than to maximise attainment of any one goal in particular. This increases co-ordination cost as there is potentially a higher demand for communication. In sum, clarity of goals and clear common goals and objectives allow team members to coordinate their behaviour and better communicate depending upon situational demands.

Classic organisation theory originally established the importance of goals in organisations (Simon, 1964) and developed the concept of organisational goals, the purposes served by goals, the multiplicity of goals in organisations (Raia, 1974), and the hierarchical nature of goals (Galbraith and Nathanson, 1978). In high-performance teams, team members tend to identify with common goals, for example timeliness, cost and quality and with the greater vision driving the project. This results in higher motivation and is a key enabler for team members to act responsibly (Ehlen, 1994; Gustafson, 1994).

Team identity

The engineers interviewed frequently spoke about the *"(...) teamy bit (...)"*, i.e. team structure, team identity, and team spirit. They appeared to closely associate the concept of communication with the way the team is organised and composed. In particular, they frequently mentioned a certain team spirit or team identity as one success criterion for communication and developing a sense of community as a key to effective project teams.

This sense of community demonstrates sensitivity to differences, thereby establishing ground rules and agreement among team members for how the team will work together (Tajfel, 1982; Syer and Connolly, 1996; Lane et al., 2001; Macmillan, 2001). Creating a sense of community or belonging leads to commitment to the team and common goals and objectives while doing individual tasks.

Design reviews, lessons learned, and best practice - reflection

Daily practice left the engineers with little time to reflect. Comparison with other projects is a means to avoid 'reinvention of the wheel' as well as to ensure shared understanding or to get everybody 'on the same page', as one participant phrased it. Best practices/lessons learned/project reviews are materialisations of team reflection. The engineers referred to 'design reviews' and 'lessons learned' sessions as activities and 'best practice' databases as an outcome of lessons learned as helpful to critically reflect on what and how design tasks should be performed. This reflection shaped how they communicated.

The beneficial effect of self-reflection in teams has been emphasised by several authors (e.g. Dörner, 1996; Blickensderfer et al., 1997; Badke-Schaub et al., 1999b; Valkenburg, 2000; Stempfle and Badke-Schaub, 2002). Stimulating designers' reflection on the design process they are part of is necessary to understanding and improving the design process. Reflecting on the design situation, implicit choices can be made explicit, such as design rationale (Aurisicchio, Bracewell and Wallace, 2013). This can improve communication between designers and stakeholders and can result in a better integration and coordination of different aspects of a design situation (Reymen and Hammer, 2002). Ideally, reflection would also happen on a regular basis and without active external encouragement outside this institutionalised or structured reflection (Ayas, 1997; Klein et al., 2003).

4.5 Understanding – Organisational level of influence

Organisational influences operating on the design team within the organisation affect communication at team-interfaces. Organisational culture and structure influences design communication style and behaviour (Chiu, 2002). Some of the following factors could be placed under the team-related factors. In our categorisation, we followed the context within which the interviewed engineers mentioned the factor.

Table 4 Record of factors affecting communication: Influences relating to the organisational level

Level of influence	Factor	#*	Interview quotes	Literature references
ORGANISATION	**Mutual trust**	14	*"There is no way that anybody would break that level of trust as it´s the basis on which the business works so well I think." (C1-I10)*	McAllister (1995) Link (2001)
	Roles and responsibilities	20	*"I think it is more about what engineers believe their job to be and I think what a person believes their role to be determines what they will and won't communicate or even what they will and won't receive what is communicated to them." (C1-I13)*	Gratton and Erickson (2007)
	Handling of conflicts	14	*"The great way that I learnt to go about this was every time I went to a meeting that I knew I was going to get shouted, I always take hard wood with me and it works." (C1-I11)*	Hinds (2003) Wood (2006)
	Activity at interface	41	*"My opinion I think we should be more proactive then we are. A lot of the time we are in this department we are reacting to what the customer says. Part of that has to do with the amount of resource available." (C1-I16)*	Souder (1988) Cooper (1995)
	Transparency of decision making	12	*"Capturing design decisions is something that we are not brilliant at. We are quite good at capturing the reasons why we do things; we are not very good at capturing the reasons why we don't do things." (C1-I10)*	Vroom (1988) Carley (1998)
	Application of corporate vision	13	*"Our communication is influenced by whether what we are told to do fits in with the overall business strategy. That is very complicated. We might be very tied down here with problems with our intake but hydro-mechanical units that all of a sudden you get told oh no, you have to go and support your colleague on this problem and not really fully understand why but this seems to be the more crucial one. On the business side maybe this particular problem is really annoying the customer. You want the customer to select us." (C1-I5)*	Galbraith (1978) Katzenbach (1993)
	Use of procedures	25	*"I have got an arsenal of choice responses or directives to follow. Because a lot of this is (Company name) procedures and if you follow it, funnily enough, it actually works. That is based on many years of (Company name) experience." (C2-I6)*	Eckert et al. 2013
	Hierarchies	19	*"The engineering director and I do try and make sure that we go and talk to the individuals, encourage them to try and talk to us about their problems rather than let them fester or do it through three levels of management."(C1-I10)*	Galbraith (1978) Felekoglu et al. (2010)

** Frequency of occurrence in interview*

Mutual trust

The majority of the engineers mentioned trust as another factor that influences communication, and stated that trust in each other's technical skills, experience and goodwill is vital for good working relations.

Mutual trust on both the product and process sides is recognised as a foundation for effective communication (Clark and Fujimoto, 1991). This is beneficial for information sharing. Conversely, lack of trust can lead to information hiding (Wheelwright and Clark, 1992). Trust is also discussed in relation to risk of information leakage (Dodgson, 1993; Das and Teng, 1998; Hoecht and Trott, 1999:257). Many functions are attributed to trust (McAllister, 1995); trust is regarded as a basis for present and future co-operations (Link, Soth and Marxt, 2001), as an important basis for teamwork in the design process (Lowenthal, Sackett and Gillies, 1997), and as a mechanism that enables reduction of the complexity of social interaction systems (Luhmann, 1979).

Roles and responsibilities

According to the design engineers' perceptions of communication in their work environment, clarity of roles and responsibilities is another important factor influencing communication. It relieves engineers from the pressure of guessing what information is expected from them and who they have to go to in order to receive the relevant piece of advice and information. The design engineers interviewed also pointed out that they *"(...) don't really have to get involved with the politics"* when roles are clearly defined.

Without such clarity, team members are likely to waste too much energy negotiating roles or protecting turf, rather than focusing on the task at hand (Gratton and Erickson, 2007). Therefore, clarity of roles strengthens technical communication.

Handling of conflicts

What is a common and traditional way for a company of how conflicts are handled – whether they are openly addressed, whether people are blamed for their mistakes, whether conflicts are seen as challenges with the potential for even better solutions – influences the way engineers communicate and determines their activity at team- or departmental interfaces. We heard that, for example, a 'blame-culture' may lead to information hiding in case of a mishap. For handling technical conflicts, design engineers pointed to a way of addressing conflicts by using physical representations such as 3D functional prototypes (see also *representation*).

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Many conflicts in the work place occur between individuals who share similar goals but disagree over the means by which they can be achieved. Handling and management of conflicts (Wood, 2006; Hinds and Bailey, 2003) relates to the topic of handling of mistakes, which in the literature on organisational behaviour and high performance teams is also referred to as ‘error correction’ or ‘team culture’. A characteristic of successful high performance teams is a certain way of handling the fact that someone made a mistake or error. When errors are discovered, they are quickly and reliably corrected. It is not focused on the question of who caused the error but how it can be resolved (Shirley and Morton, 1999).

Activity at interface – reactive or proactive

Communication patterns between teams are influenced by whether teams are predominantly reactive or proactive. For instance, as mentioned especially by interviewees at the information technology producer, when software is released to the customer, code ownership changes from the software development team to the service support team. The software development team moved on to work on the next new release whilst the support team was still predominantly concerned with a previous release and would be exposed to issues connected to the new code only after significant time has passed. This asynchronicity creates a disconnect and affects communication.

A large body of research indicates that the more the product development team members are connected to each other and to key external parties, the more successful the project is going to be (Tushman and Katz, 1980). Inter-departmental understanding is thus a strong correlate of new product success (Cooper and Kleinschmidt, 1995; Souder, 1988).

Transparency of decision making

The engineers reported that they would often hear through the grapevine what had been decided, leaving them unsure whether they were supposed to know, who else should know, and whether they would be allowed to pass information on. The engineers did not always know how and when a decision was made and what the rational had been. As such, the issue of ‘transparency of decision making’ stood out.

One of the major activities of organisations is decision making (Carley, 1998). There are mainly two topics of concern within the research on organisational decision making. The first is the way decisions are made (Vroom and Jago, 1988) and the second is the issue of transparency (Ancona, Bresman and Kauefer, 2002).

Application and translation of corporate vision

In the interviews, the design engineers pointed to many parallel discussions between different teams and other stakeholders. These multiple strands of discussions and negotiations were influenced by the corporate vision and the application or translation of that vision. In turn, the vision – or what the organisation intends to achieve at some point in the future – influences how designers address stakeholders they interact with and how they share information.

Ideally, different functional areas within an organisation have complementary goals that are derived from a set of general, organisation-wide goals. In practice, however, overall goals are often broken down into specific functional objectives that might conflict with each other (Pinto et al., 1993:1284). Individual project goals and objectives must be clearly defined and aligned with the overall goals and vision of the company. This includes the general overall purpose definition as well as specific performance targets to provide clear directions for the team members (Katzenbach and Smith, 1993; Gustafson, 1994; Shirley and Morton, 1999; Castka et al., 2001).

Use of procedures

In the companies investigated, engineering and quality procedures that are supposed to be followed were available on a document management website or filed in folders and placed on shelves openly available to all. For the engineers interviewed, the use of procedures was seen as vital for communication among themselves, with other business units or with project partners from other organisations. Following procedures eases communication, so the interviewees' response.

Procedures are seen as important in engineering design communication, as they capture and depict the desired way to approach certain tasks, determine who becomes involved in particular topics, and regulate the flow of information (Eckert et al., 2013).

Hierarchies

Hierarchies affect communication. Hierarchical structures within a company can be an enabler as well as a barrier. The position a designer holds can create and constrain opportunities in terms of availability of information. The interviewees commented that hierarchies are specifically important for communicating between different departments, particularly if employees would not know each other in person. Comments further suggested that hierarchies are specifically important for communication between designers and design managers as a technique to address conflict. Design engineers referred in their answers both to top management as well as to their direct project managers.

Business planning literature differentiates between three levels of hierarchies with respect to details of questions and decisions. The strategic level with decisions on resources, time and money made by top or senior management (Felekoglu et al., 2010), the tactical level with decisions on how to execute a strategic plan considering planning for obstacles, setting the general timetable, and the operational level involving the team in finding answers to detailed who, what, when, where, how of management questions.

4.6 Summary and discussing interview findings - potential intervention opportunities

The industry examples reported at the outset (Figures 1 and 2) and have shown that many of the factors are related or affected by each other. Literature, discussing the different factors, is often not connected as the different research communities have their respective focal points. Grossly simplified, information system and knowledge management research often focus on the information content and information flow, whereas researchers in Artificial Intelligence are very conscious of the role of representation in understanding and acting on information. A perspective informed by social psychology might focus on actions of an individual whilst a sociologically informed perspective looks at how teams collaborate. Our main contribution is to combine these factors to enable engineers and managers to reflect on their technical communication in a broader way than is currently done and to give engineers and managers the opportunity to address factors under their control.

Influences may be beyond any individual's control, e.g. global economic developments in example 1. The behaviour of the engineers in example 1 (Section 2.1) was strongly influenced by the fear of further redundancies. While senior management would probably not be in a position to remove this concern, they could, however, be transparent about the criteria that might lead to redundancies. This brings us to the second contribution of this paper: factors as levers for intervention. Not everybody has the power to affect all factors as influence rests on specific levels of management. For example, company management at the top level may define the basic reporting structure of the organisation (hierarchies) and may set the goals and vision of the company. For example, top management in example 2 did recognise that they had set conflicting goals. The managers in example 1 could generate procedures that assured that R&D work is slotted smoothly into production and include collaboration in their performance assessments of both groups, thus avoiding a conflict between the two groups. Within these constraints, teams may decide how they apply and contribute to the company vision within their own remit of tasks. Functions, such as human resources, or process excellence groups develop procedures and guidelines which help individual engineers understand their job role and guide how they are meant to interact with each other. These guidelines also have an influence on how a team works and how certain tasks are to be approached, e.g. lessons learned or documented best practices are factors often defined by the organisation but left to the discretion of a team for execution. Team managers can foster collaboration within a team. They may generate conditions within which an individual works. However, how an individual works often depends on his or her willingness to engage with the work processes. Individuals themselves need to understand what is expected of them and what they need from others. In example 2 a frank discussion between the spares and the production manager made mutual expectations clear. Individuals, as the manufacturing managers in example 1 are also responsible for acquiring and providing information. Responsibility for representations rests on all levels. Whilst individual engineers may decide which notations and terminologies are most suitable for the task and interaction partner, the basic choice of software tools and thus representations they provide is often decided at the corporate level.

Communication is always contingent and never perfect. In each communication situation something could be better. However, detrimental effects of, for example, lack of formal structures or leadership are often compensated by the enthusiasm and social skills of individuals. Similarly, individual idiosyncrasies can be mitigated by other team members' facilitation skills. Yet, this only works to a certain extent. If some factors are completely dysfunctional it is very difficult to establish effective communication. For example, if lessons learned are not in place or procedures are not adhered to and there is high staff turnover, information will be lost and the company is likely to repeat mistakes that have already been made in the past. Managing communication can sometimes be achieved by removing obstacles that can easily be identified, e.g. ambiguous representation can be disambiguated or incompatibilities of software tools can be fixed. In general, however, a big step towards improvement of communication can be taken through improvement of communication diagnosis. Communication diagnosis in turn can be improved if individuals and teams understand their own responsibilities for paying attention to factors influencing communication and thus help generating a work environment in which the elicited factors are considered.

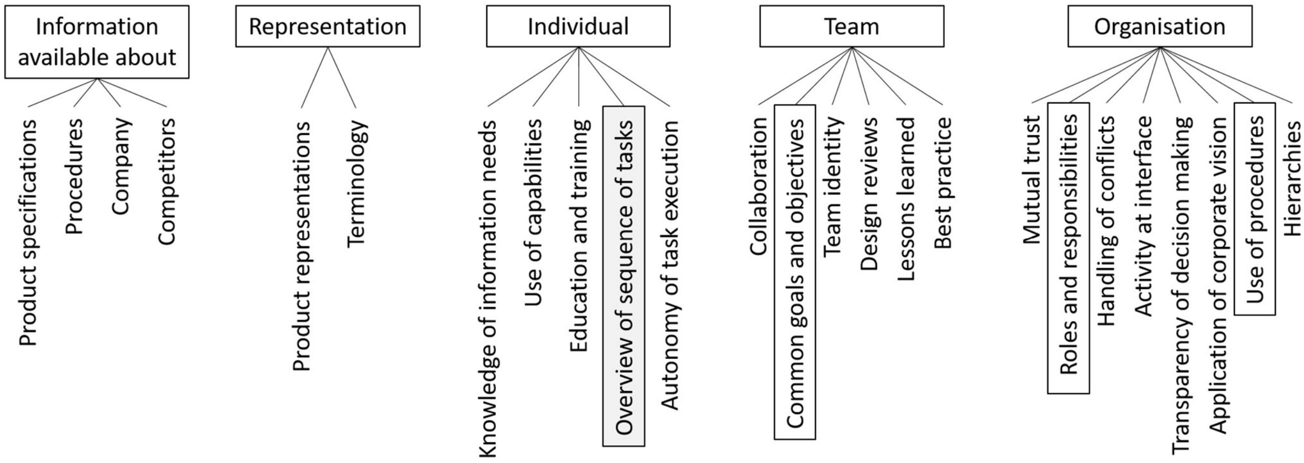

Fig. 4. Factors affecting communication. The factors affecting the example in Fig. 2 are framed. Overview of the task sequence is the only factor under the immediate control of an individual engineer.

In summary, we argue that factors influence communication on either an individual, a team or an organisational level, meaning also that stakeholders from different hierarchical levels in an organisation are able to intervene at different points. For example, an individual alone can do little to increase mutual trust in the organisation overall. Yet, they can make it their business to inquire about the information needs of others and to proactively inform others, for example, of changes to product data or regulations. Fig. 4 connects to the example of a communication problem between Service Support and Production/Spares provided at the beginning of the paper (Section 2.1 and Fig. 2) and illustrates how the factors elicited can help interpret a communication situation. In this particular example as observed in industry, while several organisational factors play a role, the engineers can only directly work on acquiring a better overview of the task sequence while the other influencing factors observed are beyond the direct remit of an individual engineers' control.

5. Implications for design practice, research, and education and outlook

In this article, we offer examples from industry (in particular in Sections 2.1 and interview results in Section 4), and, calling for appreciation of the range of factors that influence a particular situation, provide a platform for diagnosing communication situations, for examining factors influencing communication in more detail, and in going forward, for devising improvement measures, and for formulating research hypotheses about design communication and design performance.

Design performance is affected both by technical characteristics of the design and the processes and organisation of communication at a number of interfaces, for example between individuals, within and between teams and departments in a company, and across companies. Guided by Luhmann's characterisation of communication as a three-fold selection process of information, utterance, and understanding and based on observation and 62 interviews with industry practitioners in three case companies, research presented here provides a set of empirically elicited influences on communication at such interfaces. Our main study contributions to current knowledge for design practice, research, and education are included in what follows, providing new vistas also for follow-on work.

5.1 Implications for design engineering and –management practice

Firstly, this study contributes to current knowledge by unpacking what engineering communication itself is influenced by and thus providing intervention opportunities, which has so far not been in focus.

Within the remit of the empirical data underlying the results, it is our proposal that the factors presented in this paper can serve as diagnostic guidance and as support for taking actions for project design engineers and for project leaders. Concrete actionable insights include that when encountering situations in which participants are not communicating adequately or sufficiently, practitioners in industry might ask: *"What leads to such a situation?"* and use the factors as guidance in systematically investigating causes for problems. For instance, they might ask: *"Are the set goals and objectives mutually supportive"*, or *"are participants involved aware of their respective goals"*? No two people will perceive the factors in the same way. Knowing how colleagues perceive factors and knowing if they are at all aware of them will enhance reflective professional practice.

A first step is recognition that a communication breakdown could be a symptom as much as a cause. This research encourages managers to look beyond the perceived communication problem to the wider organisational context within which the design process is situated. Connecting to example 1 (Section 2.1), it would not have helped to look into e-mail etiquette and formulation of e-mail messages. The root to the solution lay elsewhere in the wider organisational context, namely the conflicting goals and objectives set at the time. Results thus also assist practitioners in finding causes for problematic situations and in more effective engineering project management.

The list of factors can serve as a basis for subsequent interventions for working towards a desired situation. Although developing new products is affected by many uncontrollable external factors and a situation may often appear overwhelming, managers can improve the way they evaluate their practices by understanding the factors that influence communication and contribute to navigating complex design processes and thus perhaps reduce potential negative effects on time, cost, and quality. Whilst the relative importance, frequency of occurrence and strength of factors will vary at different interfaces and over time, the factors themselves have been described at a level of generality that directs the engineering designers' reflection but should be applicable irrespective of time, industry sectors, organisation size and type, developed product, and design phase.

5.2 Implications for design research

Secondly, this study contributes to current knowledge by using and raising awareness for a system-theoretic notion of communication that has to-date not been accentuated and operationalised in engineering design literature. Using a systemic notion of engineering communication frames communication differently and provides a starting point for theory-building and at the same time for formulating hypotheses for design performance.

Challenging the prevailing conceptualisation of communication in engineering, we suggest that communication does not only play a significant role in determining design project success but that it is vital to the continuation of social systems such as designing. Building on Luhmann, ensuing or follow-on communication is needed to progress design. This moves the discourse and theory-building on communication in design from a 'communication as a problem' that has to be fixed to 'communication as the basis for existence of social systems' that we better make sure it does not stop.

It further adds to the conversation in engineering design communication from currently being focused either on the study of micro-level foundations in specific situations or macro-level conclusions of communication being 'crucial', without additional unpacking of what affects communication, proposing an actionable meso-level that offers a more nuanced articulation of factors influencing the communication process and thereby providing intervention opportunities to affect change. Such an operationalisation of a systemic notion of communication enables on the one hand to think in connections, to formulate hypotheses and to think through how things might play out, and as such, to focus efforts on what is changeable. On the other hand, it 'forces' thinking about the boundary around which a change can be made. Understanding the needs and aspirations around one's immediate surroundings, one can change what one has control over in a beneficial way to the whole rather than just your own niche. Both aspects, we conjecture, provide the necessary condition for success, the space for follow-on-communication (see also Section 2).

5.3 Implications for design education

Educators may also benefit from using results in teaching design management, design process improvement, integrated product development, or human behaviour in design (e.g. Lindemann, 2003). The industry example at the outset of the paper and subsequent influences elicited here serve as indicators for possible communication problems and (knowledge) glitches (Hoopes and Postrel, 1999), and potentially also for assessment of current collaborative practice in a design chain (Personnier, Le Dain and Calvi, 2011). The findings of this paper are also envisaged as a call to action that when teaching, it is fruitful to point to the differences in perception of such factors among team members and raise awareness of potential discrepancies and their consequences. Awareness of individual factors such as *overview of sequence of tasks* and changes associated with individual factors may allow for a reduction in adjustment and training cost of engineers when starting new job appointments.

5.4 Outlook

Although described separately here, factors are inter-related or overlapping. As an outlook, a research topic going forward would be to investigate the effects of all the factors simultaneously to uncover the relative contribution of each factor in collaborative designing and new product development communication. A start for which has been made by the authors (Maier et al., 2008) in looking at correlations between factors where in particular the factors roles and responsibilities and trust exhibited high correlations and thematic centrality. Seeing design processes as communication processes (see also (Crilly *et al.*, 2008)), it would be valuable to determine how successful that process is, perhaps by taking factors presented here as moderating influences for measuring product- and project success. For researchers focusing on organisational interventions, the results serve also as input for developing communication and collaboration health checks for engineering design.

Moreover, the structure of factors elicited through interview in this study could be employed in conjunction with research focusing on other aspects of design and work processes in general, applicable to a number of areas in design, e.g. engineering design, industrial design, and service design. Specific topics are, for example, competences and skills for collaboration (e.g. Kleinsmann et al., 2012), team effectiveness and team member satisfaction (Barczak and Wilemon, 2001), relational-co-ordination and social capital (Bolton, Logan and Gittell, 2021), human factors engineering in design (Broberg, 1997) for collaborative global product development (Eppinger and Chitkara, 2006), joint innovation and collaborative innovation networks (Gloor, 2006). Combining these investigations can lead to a comprehensive framework for studying and supporting human behaviour in collaborative design with a particular emphasis on theory-building for and the practice of engineering design communication and thus design research (Cash, 2018).

6 Conclusions

Many researchers have studied collaborative design processes and interface management in product development to understand and support practice. Communication has often been identified as a key issue and of highest importance for design project success. This paper has shown that communication in design is ‘determined’ by a vast array of factors and these factors interact with one another in a complex and unpredictable way. Based on a series of 62 interviews with practicing design engineers, this article has sought to categorise and represent those factors that are most influential in collaborative design as identified by design practitioners. The range of factors listed is representative rather than exhaustive. Factors are not differentiated into ‘enablers’ and ‘barriers’ as they can act as both. This paper has argued that a communication problem is often symptomatic of underlying issues which may be related to informational, representational, individual, team, and organisational issues. This paper thus broadens the thinking of engineers who reflect on communication in their organisation and look for areas they can influence, e.g. in the form of ‘levers they can pull’. By applying a theory informed conceptualisation of communication in the context of engineering design and development, and by empirically delineating factors that influence communication, this study is novel and lays the foundation for a systemic and systematic evaluation of communication in engineering organisations.

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