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A meta-model for communication in engineering design

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This paper seeks to address different ways of conceptualising communication – a mechanistic and a systemic view. The views are considered complementary rather than exclusionary. A meta-model of how communication in engineering design can be conceptualised to analyse communication issues in industrial practice is proposed. The model combines an information-centred view reflecting the exchange of information with interactional and situational aspects. It is intended to provide the backbone of an audit method with which the current ('as-is') as well as the desired ('to be') communication situation in a company can be diagnosed. The conceptual meta-model for communication in engineering design presented here is part of a wider research project that aims at assessing the current and the desired communication situation in design teams by raising awareness and providing a platform for reflection.

Keywords: Complexity; Communication; Mechanistic; Systemic

1. Introduction

The design of a complex product, such as a helicopter or a jet engine, requires the co-ordination of many different individuals and groups of designers who are embedded in different 'object worlds' (Bucciarelli 1994), who can be located at different geographical sites and who might even work for different companies. Companies are trying to understand this web of interconnected communications in their constant struggle to meet tight deadlines, to achieve quality targets and to reduce costs. Communication has been identified as a major determinant of success or failure in design processes (Hales 2000), which in turn – be they mechanical or software – are understood to be complex technical and social processes (see for example Minneman 1991, Hubka and Eder 1987).

The concept of 'communication' brings different connotations to mind among different people. It may at first sight appear rather straightforward and commonsensical. If we were to address colleagues at work with a question such as 'How is the quality

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of communication in your department?' we will receive many different answers. By asking this seemingly trivial question and listening to the responses, we will notice how multi-faceted communication is and how different communication can be seen, how different aspects will be emphasised and how different a story can be told. The replies might give attention to the type of information transmitted, how people interact, who is conversing with whom, what is the context of communication and whether the individual is giving appropriate and consistent weightings to different aspects of communication, such as information transmitted, interaction modes and the situation it takes place in. We seldom ask ourselves whether or not the person we are talking to is drawing the same conceptual boundaries around the idea of 'communication' as we do ourselves, or as other persons to whom we might address the same questions. This is not to say that we all should have the same conceptual boundaries, but rather to point to the fact that they differ, that there are different ways of telling a story and that we should take account of the differences while communicating.

This paper seeks to address different ways of conceptualising communication. The aim of this paper is not to compare these views in terms of their efficacy in describing engineering design communication, or even guiding design communication practice, but rather to explore and show how they represent different ways of thinking about communication in design and how it could be used to diagnose communication issues in design. The underlying assumption being that different ways of conceptualising communication might go hand-in-hand with different ways of thinking about the world. The conceptual meta-model for communication in engineering design presented here is part of a wider research project that aims at assessing the current and the desired communication situation in design teams. The remainder of this paper unfolds as follows: section 2 introduces a conceptual meta-model of communication; section 3 applies this model to engineering design communication; section 4 presents a summary and conclusion.

2. A conceptual meta-model of communication

There are many approaches to categorise communication theories and models in communication studies, such as for example the ones by Fiske (1990), Craig (1999) and Littlejohn (1999). A discussion of the different categorisation schemes is beyond the scope of this paper. It is however important to note that the model proposed in this paper is a means to a different end. It shows how different ways to conceptualise communication could lead to different ways of understanding where communication problems stem from and whether communication processes in general and especially within industrial practice can be controlled. The model is put together to serve the purpose of highlighting different communication issues in practice. It is intended to alert the reader to the way communication issues could be conceptualised and based on which industrial practice intervention levels and strategies could be constructed. The authors think that the model proposed leads to a fruitful differentiation between issues of communication in empirical practice. In terms of the theoretical underpinnings, there are similarities with the soft systems methodology (SSM) proposed by Checkland and Scholes (1990). This paper, however, focuses on a communication theoretic perspective.

The model proposed in this paper differentiates between two complementary but different ways of viewing and explaining communication: One method focuses on the 'mechanics' of the process of information transmission – here termed the *mechanistic view* and depicted in figure 1; the second method considers the process of technical information transmission in its wider context of interaction, understanding and the situation – here termed the *systemic view* and depicted in figure 2. Note that the term meta-model implies that it is a model that incorporates many different models and groups them into two broad 'clusters'. For a cognitive and social process, such as communication, it is important that both ways of conceptualising communication are addressed. The two views are presented as complementary and not dichotomous. The conceptual meta-model of communication will be gradually built up through the paper, culminating in the model in figure 5 (see section 2.5).

2.1 *Transmission models: a mechanistic view*

Practitioners, especially in engineering design, often take a reductionist view of communication. They see it solely as an act of transmitting information from the sender to the receiver, where the challenge lies in the transmission of information rather than in the understanding by the recipient. They often point to practical problems in communication, such as suboptimal access to data or the incompatibility of formats. This view has its intellectual antecedents in a mechanistic worldview, which holds as its basic premises that the universe can best be understood as a mechanical system – that is, a system composed of matter in motion under a complete and regular system of laws of

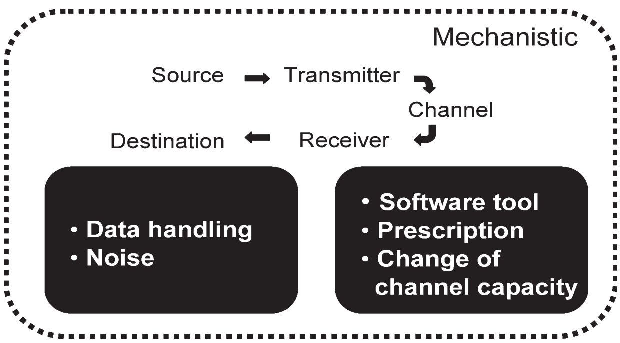

Figure 1. Mechanistic view of communication.

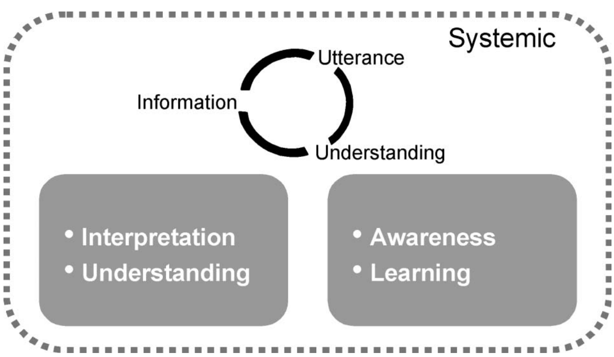

Figure 2. Systemic view of communication.

nature and that all phenomena can be determined by the properties of that matter and the operations of those natural laws. In a reductionist worldview the whole is reduced to its components and is not more than the sum of its parts (Malik 2003). It has to be noted though that there are still ways to adhere to reductionism in principle, following the argument of Simon (1983) who speaks of 'near-decomposability' (Simon 1983, p.174, 197–198): '(...) even though it is not easy (often not even computationally feasible) to infer rigorously the properties of the whole from knowledge of the properties of the parts'' (Simon 1983, p. 172).

As a representative of a way of conceptualising communication, the model presented by Shannon and Weaver (1949), which focuses on the technical information transmission, will serve as an illustration. Shannon (1948) and Shannon and Weaver (1949) proposed a 'mathematical theory of communication' that makes reference to the basic organisation of communication technology. The Shannon and Weaver model proposes that a basic system of communication may be thought of as being composed of five elements: source, transmitter, channel, receiver and destination. This model of information transmission, which was originally developed for noise reduction in electric data transmission, is a sender–receiver model that assumes that the sender sends a message through a channel that is received by the receiver like an object. The information source produces a message, which is encoded into a signal that is then transmitted across a channel. The receiver decodes the signal and the message arrives at the destination. Any interference in the transmission of the intended message through the channel is referred to as noise.

Inherent in the Shannon and Weaver model is a mechanistic, uni-directional, linear view of information transmission that does not describe communication in its entire complexity. Even though it was not intended by the Shannon, his model has inspired applications to human-to-human communication and mass-communication (see for example Reddy 1979), leaning towards the tendency that the 'right' decoding of the sender's encoded intent and intended meaning is the key to successful communication. Emphasis is put on the sender and the message. It is mostly assumed that meaning is contained within the signs used in the message and the receiver can 'extract meaning' just like opening up a parcel. The view that communication is basically a transfer or transportation of fixed messages shows up in many disguises, under several different but related metaphors such as, for example, 'the translation theory of speech communication' (Linell 1982). While the Shannon and Weaver model is intuitive and sheds light on many difficulties in communication, it ignores the individual cognitive processes of the communication partners and their interaction. Matters such as the social context in which the message is transmitted, the assumptions made by source and receiver, their past experiences and so on are disregarded. Shannon and Weaver's model works well for engineers who speak in terms of fidelity and message transmission. However, it works less well for sociologists and others concerned with the cognitive and social nature of communication (Lorimer 2002).

Shannon and Weaver never intended for the model to be applied to human-to-human communication. Semantic aspects did not play a role. Information refers only to the physical act of transmitting data from one technical system to another. The authors explicitly stated this: 'The word information, in this theory, is used in a special sense that must not be confused with its ordinary usage. In particular information must not be confused with meaning' (Shannon and Weaver 1949: Introduction). It is argued here that we need to differentiate between the purpose and usefulness of the model in the original context of electrical signal transmission and adaptations of the model in different contexts. If it is applied in different contexts, it should be noted that assumptions are inherited.

2.2 *Focus on understanding: a systemic view*

An alternative worldview started to be (re) considered, as a result of findings from the study of living systems in biology, anthropology, ethnography and ecology, second-order cybernetics and new discoveries in physics in the twentieth century. A systemic worldview focuses on living organisms or life itself and the relationships that connect all living things and ecology. Basic tenets are that reality is not seen as being composed of discrete building blocks but rather as webs of relationships that are interrelated and interdependent. Furthermore, the observer cannot be separated from the observed. Prediction, control and certainty are superseded by probability, influence and uncertainty. Emphasis is put on visualising patterns and processes as opposed to singular events and their outcomes. Put in abstract terms, systemic theories assert that there are certain wholes, composed (say) of constituents A, B and C in a relation R to each other. All wholes composed of constituents of the same kind as A, B and C in relations of the same kind as R have certain characteristic properties. However, A, B and C are capable of occurring in other kinds of complex systems in which the relation is not of the same kind of R. Characteristic properties of the whole cannot be deduced from knowledge of the properties of A, B and C in isolation (Broad 1999).

As Watzlawick *et al.* (2000) point out, communication is 'content' plus 'relationship'. Content is 'what' is actually said, while relationship is 'how' it is said. A mechanistic view of communication focuses on the content side. A systemic view of communication adds the aspect of creating meaning and the creation of a relationship through communication to the communication process (Thompson 1984).

Another theoretical point of departure for a systemic view on communication is illustrated with Luhmann's sociological systems theory (1995). Luhmann's concept differs considerably from the notion of communication as mere information transmission from a sender to a receiver. Building on the speech theories of Bühler (1934), Luhmann conceives of communication as a combination of three aspects: (i) 'information', (ii) 'utterance' and (iii) 'understanding', each of which Luhmann conceptualised as selection. In accordance with Shannon and Weaver (1949) he defined information as a selection from a repertoire of possibilities: every communication selects what is being communicated from everything that could have been communicated. With utterance Luhmann refers to the form (mode and media) and reason for a communication: how and why something is being said. It can be stated that utterance is the selection of a particular form and reason from all possible forms and reasons. Understanding is conceptualised as the distinction between information and utterance. For a communication to be understood, information has to be distinguished from utterance: what is being communicated must be distinguished from how and why it is communicated. For example, if designer A says to designer B 'I have just completed the failure mode and effect analysis (FMEA)', designer B has to distinguish the information ('I have just completed the FMEA' and not 'I have not completed the FMEA') from the utterance (the words designer A is using and the reason why he is saying it: e.g. designer A wants to indicate that designer B has to act upon it or that designer B should leave him alone and not press him anymore; he is not saying it in order to obtain any advice on what to do about it).

While most communication theories refer only to the first two elements – information and utterance – in Luhmann's concept, the third element – understanding – plays a central role. Instead of approaching communication from an 'intended meaning' of the communication, Luhmann reverses the perspective: (the meaning of) a communication is ultimately determined through understanding. Luhmann writes "Communication is made possible, so to speak, from behind (...)" (Luhmann 1995, p. 143). Baecker explicates this by saying: '[This principle states] that not the speaker but the listener decides on the meaning of a message, since it is the latter whose understanding of the set of possibilities constrains the possible meaning of the message, no matter what the speaker may have had in mind.' (Baecker 2001, p. 66).

A central point in Luhmann's concept of communication is that the three selections (information, utterance and understanding) form an 'insoluble unit'. This unit can be divided analytically into its three components (for example by other communications), but only as a unit does it constitute a communication. As a result of this, a communication – as this unity of the three selections – cannot be attributed to any one individual. Instead communication constitutes an emergent property of the interaction between many (at least two) individuals. Although individuals – or 'psychic systems' as Luhmann would say – are necessarily involved in bringing about communication, the communication cannot be understood as the product of any particular 'psychic system' alone.

In order to render Luhmann's concept of communication more precise, we have to take another look at his concept of understanding. With understanding, a communicative event – as the synthesis of the three selections (information, utterance and understanding) – is complete. Understanding, as mentioned above, is the distinction between utterance and information; but whose understanding is of relevance here? It is the understanding implied by the ensuing communications – in the same way as the concrete meaning of a word in a text is only defined through the following words in the text. Thus, the meaning of a communication, i.e. what difference a communication makes for later communications, is only retrospectively defined through the later communications. This retrospective determination of the communication, through ensuing communications, is connected with a fourth type of selection: acceptance or rejection of the meaning of communication. This fourth selection is already part of the next communication. Luhmann sees communication as a self-organising social process.

According to Luhmann, successful communication is highly uncertain (Luhmann 1995) because it depends on many contingencies during the threefold selection process of communication. The communicators have to (i) choose the information they would like to transmit out of many other possibilities: (ii) decide upon an adequate way of transmitting the message and (iii) the communicator at the receiving end selects a possible way of interpreting and understanding the message. Selections or decisions can be conscious or subconscious. All communicators have to be aware of these contingencies, which place a high cognitive load on them.

2.3 *Communication problems*

After differentiating between different viewpoints as epitomised by Shannon and Weaver (1949) and Luhmann (1995) for conceptualising communication, we will continue by looking at the issue of communication problems. Figure 3 shows how the different models account for communication problems.

For the mechanistic side (right box of figure 3) problems of communication arise owing to noise in the channel, technical problems with data handling and insufficient or incompatible information systems. A systemic point of view attributes communication problems for example to the fact that each communicator has a different understanding of the information transmitted and henceforth interprets it differently (left box of figure 3).

2.4 *Control or influence of communication?*

Can communication, and for that matter a product development system, be controlled? The mechanistic transmission models (left box in figure 4) seem to emphasise the fact that communication processes can be controlled; for example by increasing the bandwidth of a channel. The preferred solution seems to be a prescriptive method or some computer tool, i.e. groupware, technically to enable and facilitate information exchange. This is adequate for an infrastructural problem with information transmission.

Viewing communication as an autopoietic system ('autos' = self and 'poiesis' = creating) as exemplified by Luhmann (1995), the (sociological) system-theoretic modelling of social systems and communication is followed. Thus, the conclusion could be made that an increasing emphasis on self-organisation and self-steering within certain limits means that behaviour can be steered from the outside only to a very moderate extent. Influence, however, is possible if it is possible to understand and connect to the internal logic of a system, i.e. the components and its connections and its specific rules by which it operates. The preferred solution seems to be to raise awareness and engage the designers in an ongoing learning process.

Uncertainty in communication is the result of acomplex interaction between the communicators and the communicators and their respective environments. Environment refers to the system theoretic notion of environment of a system. Baecker (2001), following Luhmann (1995), adds to this line of thought in saying that there is an inescapable ambivalence inherent in communication which functions as the precondition for the fact that communication cannot be completely determined, let alone controlled.

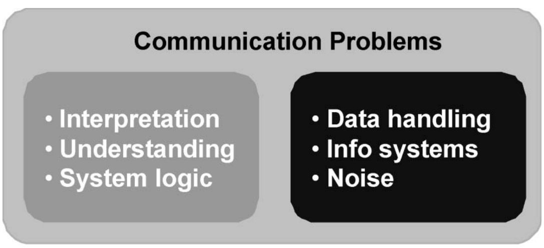

Figure 3. Where communication problems stem from.

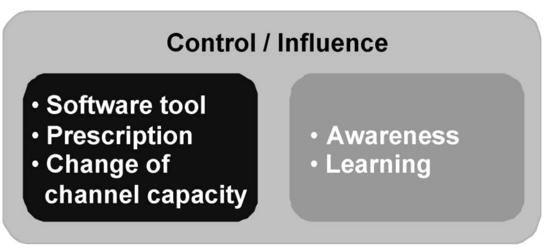

Figure 4. How communication can be controlled or influenced.

To complicate things further, uncertainty is also present in all design activities (Earl *et al.* 2005). To conceptualise communication and design as complex processes with uncertain elements makes it inherently difficult to measure and predict. Furthermore, to view the product development process as a social process in the system theoretic sense means that the process is inherently non-deterministic and cannot be controlled completely. However, it can be influenced, if the disturbance or perturbation addresses the system with the right 'language'.

2.5 *Information transmission embedded in understanding*

To reiterate, this paper does not argue that one way of conceptualising communication should be neglected to favour the other but rather both methods – a mechanistic and systemic view – need to be considered. If we want to describe and explain the behaviour of any whole in terms of its structure and components, we always need two independent kinds of information. We need to know (i) how the parts would behave separately and (ii) the law or laws according to which the behaviour of the separate parts is compounded when they are acting together in any proportion and arrangement (Broad 1999). Applied to communication in engineering design, we do need to know how an information systems architecture works (inner boxes in figure 5) but at the same time, we need to know how it is used in context by the designers (outer boxes in figure 5). The mechanistic view (inner dotted line and inner boxes of figure 5) is therefore seen as embedded in the systemic (outer dotted line and outer boxes of figure 5).

The systemic worldview of considering the whole as more than the sum of its parts stands as an alternative frame of reference when contrasted to the worldview of classical physics based primarily upon the method of analytical reductionism, or of breaking the whole down into its parts. A systemic view that focuses on understanding is seen as encompassing, in a sufficient but non-exclusive manner, a broad range of information that falls within the purview of a mechanistic worldview.

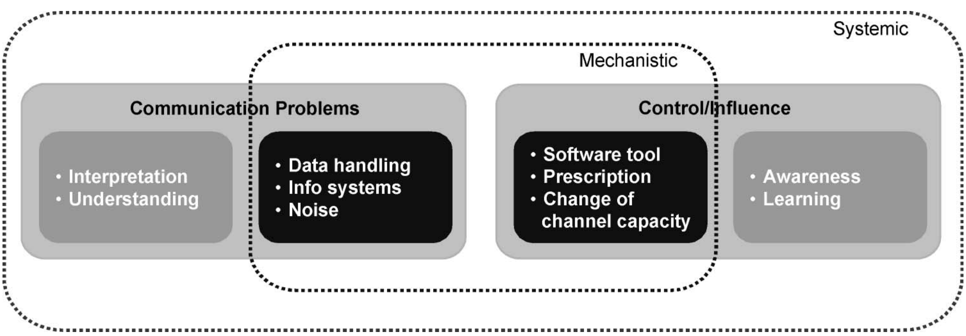

Figure 5. Mechanistic and systemic conceptualisations of communication problems and control/influence of communication.

3. The model applied to engineering design communication

In the previous sections we considered the different elements of communication which, taken together, form a web of communication that is difficult to understand and influence. In this section we now try to apply the model to engineering design practice.

Communication in engineering design can be understood in many ways. Here we are dealing with the juxtaposition of technical and human aspects, which can sometimes not be clearly demarcated. A brief characterisation of engineering design communication follows.

3.1 *Engineering design communication: technical aspects*

How can engineering design communication be characterised? Even though the subheadings of this paper suggest that technical factors can easily be split from human factors in designing and henceforth in engineering design communication, they are intertwined. An example clarifies this statement. Suppose two companies are working together on the design of a system, each company being responsible for one or more components and dependent on each other's design outcome. Company A has the policy that only completed and finished drawings will be uploaded into the collectively accessible shared database. To company B, however, there are several different ways to interpret this behaviour – they might think that company A does not release any information and never keeps on time or does not do any work. In contrast, company B, has the policy that everything from meeting notes to concept sheets to different drawings – goes 'online' immediately for people to access and be 'in the loop'. Henceforth, company A might view company B as unstructured and unprofessional because nothing is seen and released as definite. Is this now a problem, with no data for one company, and preliminary data for the other, – a seemingly technical aspect – or is this attributed to the human aspect of not communicating company policies in the first place?

In order to design a solution to a practical problem, a designer (from Latin '*ingeniosus*' = skilled) has to possess technical knowledge and skills, such as knowledge on mechanical, thermal, fluid and electrical principles, numerical methods and simulations to name a few. This yields an enormous amount of data, which designers have to take into consideration and which have to be depicted in an adequate way. What is essential about (engineering) design communication are visual representations. Designers visualise their ideas and solutions concepts in sketches, technical drawings, computer models, mock-ups, prototypes, etc. – factors termed by Henderson (1999) the 'visual culture of engineers'. 'A major portion of engineering information is recorded and transmitted in a visual language that is in effect the lingua franca of engineers in the modern world, (Ferguson 1994, p. 41). There are many features and qualities of a product or an object to be designed in general that a designer cannot reduce to unambiguous verbal descriptions, therefore, they are dealt with in the mind by a visual, non-verbal process.

Engineering design has a wide spectrum of representations, such as Gantt charts, bills of materials, requirement lists to two-dimensional sketches, different types of drawings, three-dimensional computer-aided design (CAD) models and physical prototypes. Bucciarelli (2003, p. 21) crosses the verbal/non-verbal demarcation. He construes language – the engineering language – in the broadest terms and includes sketches, prototypes, charts, even a computer algorithm as elements employed in the productive exchange among participants, i.e. in engineering design communication.

3.2 *Engineering design communication: human aspects*

Designing is a social process of negotiation and iteration which is marked by uncertainty (Suh 1999; Bucciarelli 2003, Earl *et al.* 2005). Unquantifiable judgements and choices account for many elements that determine the way a design comes together (Ferguson 1994). As Earl *et al*. (2005) state: 'Uncertainty is present in all areas of design and designing (products, processes, users, and organisations).' The authors differentiate further between 'known' and 'unknown' uncertainty. 'Known' uncertainty refers to variability in past cases. 'Unknown' uncertainty refers to the fact that it is not expected or 'factored in'. Both types of uncertainties span across 'uncertainties of data' and 'uncertainties of descriptions'. The status of data are often not known, i.e. whether it is accurate and complete. Uncertainty of description refers for example to the selection of the element to put in a model and the choice of naming.

To connect this characterisation of uncertainties in design to Luhmann's modelling of communication, the above mentioned 'uncertainties of data' and 'uncertainties of description' could be compared with Luhmann's first and second selection process ('information' and 'utterance') as part of communication processes. The designer has to decide, among many other possibilities, which data and piece of information to choose. Furthermore, designers decide upon the choice of media with which to communicate the selected information or with which to represent the selected information. To add to this, there is Luhmann's third selection process – understanding – which makes a communication process complete and which carries its own contingencies in the form of interpretation.

To elaborate further on the specifics of engineering design communication, we have to take a step back and look at the basic task of a designer. It could be said that he or she transforms information. Many engineers carry out tasks with clearly specified problems and clear procedures for solving them. They use schematic and mathematical descriptions of their work that can be understood through established conventions. However these descriptions do not carry the rationale for the way in which they have been created. This understanding needs to be generated through a much richer social interaction, in which designers negotiate the understanding underlying the representations that they generate.

In order to succeed in this 'translation task' designers collaborate with many different other designers or colleagues from other departments, such as for example manufacturing, marketing or procurement. Designing is rarely a solitary activity. It is a social interactive process. Complex products are designed by teams of people, perhaps in single companies but more often distributed through the supply chain. An extreme example is the design of a new aircraft, where thousands of engineers may work on the design of a new aircraft engine in a first-tier supplier company. In addition, dozens of engineers work on the fuel pumps as second-tier suppliers, and this company will in turn have its own suppliers (Eckert *et al*. 2005).

In conclusion designing involves collaboration and negotiation. Communication is essentially underlying – speaking with Luhmann – constituting these social processes. It is kept alive through ensuing communications.

4. Summary and conclusion

This paper highlights complementary but different stances to viewing and explaining communication. It furthermore shows that underlying these models are different worldviews, which are reflected in thinking and writing about communication. We may recapitulate by saying that communication in engineering design encompasses the technical process of information transmission but if stopped there, it would not sufficiently constitute communication. It involves – according to Luhmann – a threefold selection process – each selection being highly contingent. Design is a technical and social process and it is henceforth necessary to consider the technicality of information transmission as well as the richness of the social-technical interplay inherent in communication processes.

The meta-model suggested in this paper informs a communication audit method with which the current ('as is') and the desired ('to be') communication situation in industrial practice can be diagnosed (see Maier *et al.* 2006). The conceptual model is useful in selecting topics that need to be looked at in detail, such as data storage and retrieval and the technical infrastructure for information transmission (inner boxes in figure 5 referring to the mechanistic view of communication) as well as awareness of for example design process tasks (outer boxes in figure 5 referring to the systemic view of communication). The model is furthermore useful in guiding the choice of an audit method and procedure. If the systemic view is emphasised, the conclusion is reached that a method which engages designers, raises awareness, provides an opportunity for self-reflection and self-observation facilitates a learning process. It furthermore complies with the notion that communication processes cannot be fully controlled but influenced.

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