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# ASSOCIATIONS BETWEEN FACTORS INFLUENCING ENGINEERING DESIGN COMMUNICATION

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## ABSTRACT

The design of complex products, such as aero engines or cars, requires the co-ordination of many different individuals and groups of designers. Communication has been identified by many researchers and practitioners in industry as a major determinant of success or failure in design projects. Communication is influenced by manifold factors on different levels, be it through product attributes, information and media-specific factors or factors arising from organisational and team structures, and individual activities. Understanding of associations between these factors supports successful communication management. This paper presents associations between selected factors influencing communication. It shows a network of correlating factors covering a number of aspects of communication in engineering design and focuses particularly on '*collaboration*', '*mutual trust*', '*overview of sequence of tasks in the design process*', and '*autonomy of task execution*'.

*Keywords: Communication, research and development management, concurrent engineering, product development organisations, empirical case studies in industry, representations, network of factors*

## 1 INTRODUCTION: COMMUNICATION TO CO-ORDINATE BEHAVIOUR

In design and development, products and services result from interactions among a multitude of people who work across functional, organisational, cultural, temporal, and geographical boundaries [1, 2]. In concurrent engineering, tasks are distributed among individuals and whenever possible executed in parallel [3], increasing the need for effective communication. Typically, the different participants in the design process have different competences, skills, responsibilities, interests, and inhabit different 'object-worlds' [4]. Everyone has different 'viewpoints' [5] which can lead to conflicts that need to be resolved through negotiations [4]. Functioning communication between all stakeholders – taking manifold factors influencing communication into account – is crucial for a well-co-ordinated process.

### 1.1 'Disappearing welding spots': An example from the automotive industry

An example from the authors' experience in automotive sheet metal design illustrates different influences on communication. During the early phases of designing a car body, core engineering departments need to come together to specify key parameters, such as size, weight, performance, and properties, such as stiffness, crashworthiness or manufacturability [6]. To achieve a highly efficient design process, collaboration between embodiment design (CAD) and simulation departments (CAE) is necessary [7, 8]. In particular, a number of welding spots need to be specified during the design of the automotive body. Welding spots are determined by designers in collaboration with engineers from the production planning department in order to put the spots within the reach of welding robots. The co-ordinates of each welding spot are recorded in a spreadsheet that is linked to the assembly files of the sheet metal design of the car body. All files are available through the company's PDM system. However, when assembling input files for numerical simulation, this information is not used directly by the engineers compiling these files, and it is only vaguely transferred into the FEM-model without further cross-checking. In fact, assumptions about the connectivity between different components might thus differ from the original design. After simulation, the welding spots are no longer contained in the geometry model of the individual component and the connection to the original definition of the welding spots cannot be traced anymore. All that happens whilst Design focuses on details of the component or module and Simulation focuses on specific functions, which requires them to consider more than one component or module. Lack of communication to co-ordinate activities, obvious in this example, reflects the different understandings and goals of different groups as well as lack of adherence to process steps. A better understanding of different formats of representation and information needs could improve the process.

Managers of design processes need to have a sense of where processes can be influenced. This requires understanding of how factors are connected, so that effort is not misdirected by attending to the symptoms, yet possibly ignoring underlying causes. In practice it is often possible to analyse a specific situation, however, little theoretical understanding of the correlation of factors influencing communication has been published. The premise is that effective communication co-ordinates the design process which contributes toward a good product. As communication is influenced by a whole range of factors, the aim of this paper is thus to explore associations between those factors so as to provide anchor points for communication management.

### 1.2 Outline

This paper presents a network of factors affecting communication, elicited during five empirical studies in different industry sectors. The procedures for data acquisition and analysis are described. Results in the form of a network of correlations are presented and the findings are compared and contrasted with literature for validation purposes. Particular emphasis is placed on finding a direction of influence between correlated factors. Results are critically reflected and implications for engineering research and practice are derived. The paper ends with a conclusion and suggestions for further research.

## 2 METHOD: EMPIRICAL DATA AND STATISTICAL ANALYSES

Empirical data were acquired by applying the *'Communication Grid Method' (CGM)* [9, 10, 56] in industrial case studies to provide numerical scores of engineers' perceptions of the current state about a list of factors influencing communication. Within the context of research presented here, the *CGM* functions solely as acquisition method for empirical data. In order to place further results in context, derivation of the method is described.

### 2.1 Acquisition of empirical data through the 'Communication Grid Method'

The *CGM* is based on the idea of process assessment along with maturity grids in quality management [11] and software development [12]. It is used here for the assessment of communication in collaborative design. Levels of maturity are allocated against a number of factors characterising communication. Text descriptions in the cells of the grid express different levels of maturity (Figure 1), showing the development from an initial to a more advanced state for the chosen topic [13].

Project Teamwork

*Please answer for your project team*

| | Level of maturity | | | | | |
|---|---|---|---|---|---|---|
| **Factors** | **A** | **B** | **C** | **D** | **Current score** | **Desired score** |
| **Collaboration** | Everyone looks solely after his tasks | Collaboration happens only if asked for in order to fulfil tasks | Collaboration happens proactively in order to learn from others and improve own approaches | Collaboration is constructive, happens regularly whenever necessary and there is continuous effort to improve it | [ ] | [ ] |
| **Common goals and objectives** | Not known. No thinking about it | Known but everyone follows just his own goals | Known and sometimes consideration about the way common goals can be reached through working together | Entirely clear and identification with it which is expressed in communication and continuous effort to assess and adjust goals and objectives and the way to each them | [ ] | [ ] |
| **Team identity** | There is none and it is not seen as necessary | Small groups form depending on the task and these groups get their identity through the tasks | Attitudes with respect to team identity are continuously reflected upon in order to find a common denominator | There is a strong sense of belonging to the team and continuous reflection on how team identity can be kept up and strengthened for the project | [ ] | [ ] |
| Comments | | | | | | |

*Figure 1. Example of a Communication Grid Sheet*

The factors – elicited through a combination of ethnographic case studies in industry and analysis of relevant literature prior to this research project – are evaluated to four levels of maturity based on the idea of learning types from Argyris and Schön [14] (for details, see [10, 56]). Engineers score their perception on the current (as-is) and desired status (to-be) of factors influencing communication at a certain team interface, using grid-sheets during interviews or workshops.
The *CGM* investigates a set of 54 different influences (represented by a set of factors) which are allocated to five levels of influence (product, information, individual team member, project team and organisation). These in turn are subdivided into 11 influence areas under which individual factors are subsumed, as can be seen in Figure 2. Definitions of the factors are listed in Appendix A.

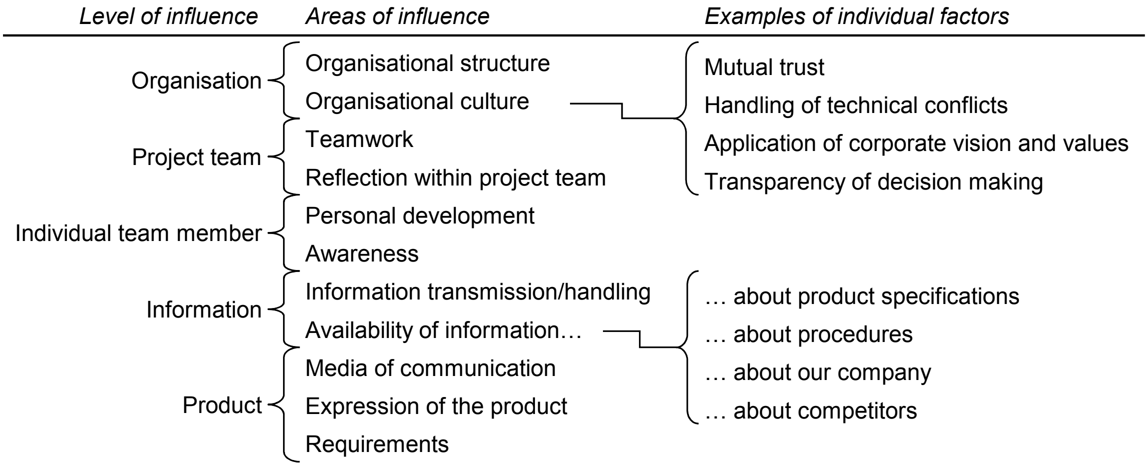


*Figure 2. Categorisation of factors in the 'Communication Grid Method'*

This research assumes that by correlating score values, an informative picture of connections among the selected factors can be drawn. Values for the desired status are not considered in this paper. To analyse communication in product development five case studies were carried out in four companies:

- A large globally operating company in information technology, developing and servicing software and providing consultancy. Communication between service support and development of one particular code-base of one software project was to be analysed. The work incorporated routine as well as innovative solutions to a problem customers found in the company's software.
- A small company producing electron beam and furnace technology, based in the UK. The 'works order' process was to be improved through an analysis of how a 'works order' flows through the company from its initial order to an offer. The focus of the audit lay on communication among the management team (engineering, manufacturing/spares, sales, service, and finance).
- A large aerospace company, based in the UK, designing, manufacturing, and servicing aero engines. Two studies within two distinct branches (civil and defense) of the company were conducted. In one project, the communication audit conducted investigated the state of communication at the interface between design and a service team of one particular aero engine. The other project aimed to diagnose the state of communication at the interface of preliminary design for one of the civil engines and the business unit designing IP turbine blades.
- A large German automotive manufacturer. The audit looked at communication at the interface between embodiment design (CAD) and simulation (CAE) . The study focused on the design of the so-called 'trimmed body' for the serial development of one of the company's vehicle series. The observed interface to simulation was that of engineers involved in developing the function 'Noise Vibration Harshness' (NVH).

In total, 38 engineers and managers completed the grid sheets in either individual interviews or group workshops (six to nine 9 from each company). All case studies were concerned with communication at a certain team-interface with regard to a specific project at a specific design phase. The definition of factors was given to all participants in the studies in order to provide a common reference point. All projects contained routine as well as non-routine design elements in order to design the product, where routineness is expressed on an axis, with the possibility of different degrees of routineness [55].

## 2.2 Exploration of inter-variable correlations through statistical analyses

Kendall's *tau-b* measure of association was used to explore the rank-ordered empirical data statistically [15, 16]. For visualisation purposes, the correlation matrix across all the participants was processed manually (see Appendix B). Out of the 54 factors originally considered, 27 factors that were present in at least four of the five empirical studies are selected in this paper. For statistical calculation purposes, factors are referred to as variables. Only statistically significant results for correlations were counted for further exploration. Categorisation of correlation was the following [17]:

- 'high' correlations from 0.60 to < 0.80;
- 'moderate high' correlations from 0.50 to < 0.60, and
- 'moderate low' correlations range from 0.40 to < 0.50.

Only correlations at a significance level of at least $p<0.05$ and those with an absolute coefficient value of $\geq 0.40$ were chosen. All of these are characterised by a positive correlation coefficient and are symmetrical. Consequently, the correlation matrix does not show which variable drives a particular correlation, *i.e.* no (directed) dependency can be deduced from the statistical results alone.

# 3 RESULTS

Four 'high' and eleven 'moderate high' correlations were found, as well as 18 correlations having a 'moderate low' coefficient. Constrained by the selection criteria mentioned above (Section 2.2), Figure 3 and Appendix B show the complete set of correlations found.

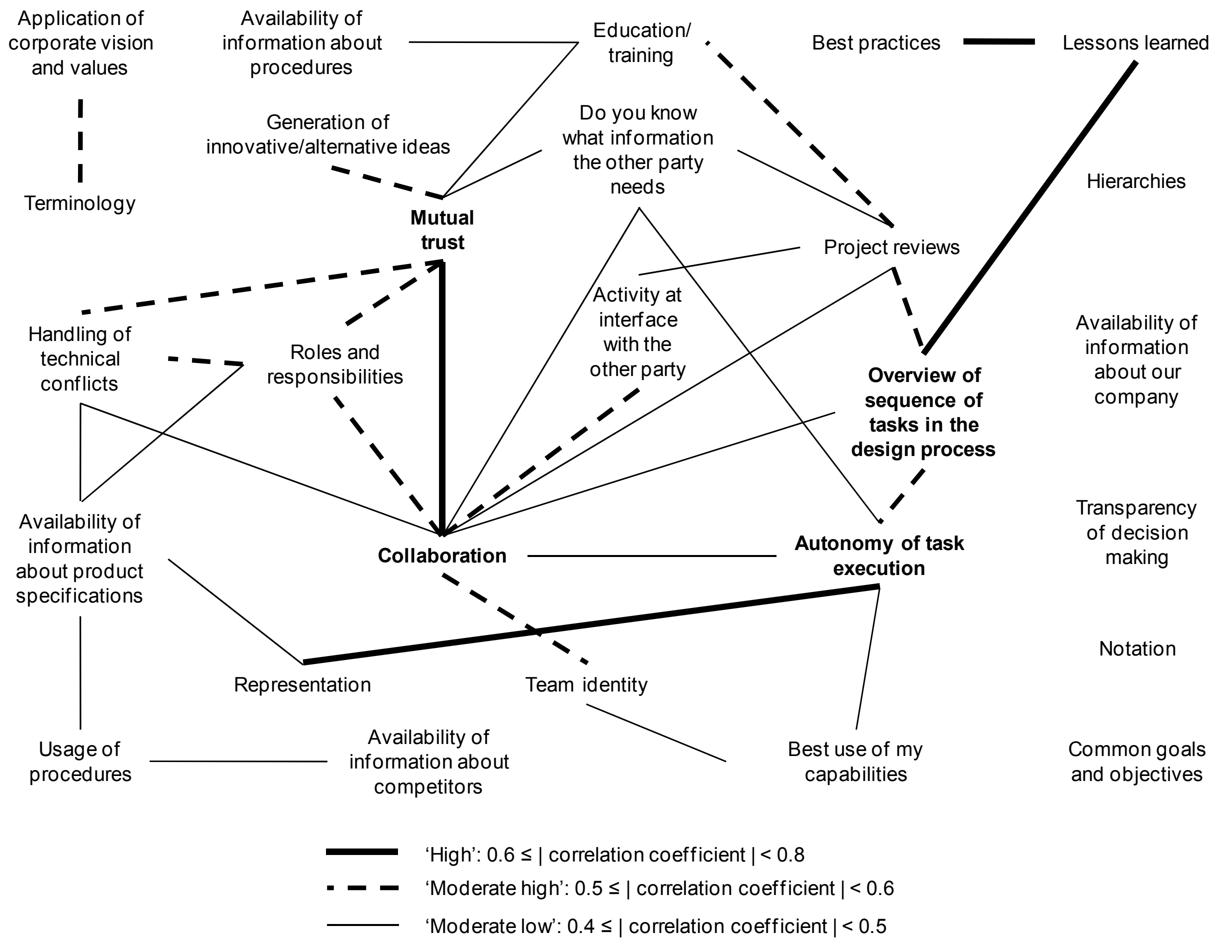


*Figure 3. All correlations*

As examples of the findings, representative instances of expected and unexpected correlations are listed below. Judgement whether findings are expected or unexpected is based on whether results are consistent with results of published studies in communication and concurrent engineering.

## 3.1 Expected correlations

The data set has been analysed looking particularly for (i) 'core variables' and (ii) 'general themes'. Examples for expected correlations are presented below.

### *3.1.1 Core variables*

Core variables are variables which show a high correlation coefficient ($0.60 \leq |\text{correlation coefficient}| < 0.80$) and correlate with a high number of other variables, as highlighted in Figure 2. Based on the selection criteria, the results thus underscore for example:

- 'collaboration',
- 'mutual trust',
- 'overview of sequence of tasks in the design process' (see Section 3.1.2), and
- 'autonomy of task execution' (see Section 3.1.2).

'Collaboration' shows correlations with nine other variables, 'mutual trust', displays correlations with six other variables, and 'overview of sequence of tasks in the design process' is related to four other variables (Figure 3). The statistically inferred importance of these correlations for design management is supported by literature.

***Collaboration*** is conceptualised as the degree, extent and nature of working together and mutual help among project team members. The importance of 'collaboration' becomes apparent as there are nine correlations containing this variable. 'Collaboration' was predominantly identified in the reviewed literature as being influenced by other variables, such as 'roles and responsibilities', 'mutual trust' and 'team identity' (see Table 1). In some of the reviewed literature 'collaboration' is also seen as the driving variable. For example Kuhn and Nelson [18] determined in their research that people *"(...) who were perceived to communicate with many other team members about tasks were more likely to identify with several identity structures relatively strongly"*.

***Mutual trust:*** Aside from the literature references in Table 1, trustful behaviour generates benefits, such as improvements of communication. As Clark and Fujimoto [19] point out, *"(...) mutual trust on both the product and process sides seem to be the basis of a foundation for effective communication"* [19]. This is beneficial to information sharing. Alternatively, lack of trust can lead to information hiding [1]. Trust is perceived as one of the most relevant success factors within the academic literature concerning commercial co-operations [20].

### *3.1.2 General themes*

Certain factors have been grouped into general themes that are listed below: 'Lessons learned' shows high correlation coefficients with both 'best practices' and 'overview of the sequence of tasks in the design process'. 'Lessons learned' and 'best practices' are taken as indicators for the importance of 'reflection'. 'Overview of sequence of tasks in the design process' is taken as an indicator for the importance of 'overview and awareness'. There are manifold accounts in the literature that support these findings in general.

***Reflection:*** The beneficial effect of reflection in teams has been emphasised by a number of authors [21, 22, 23, 24, 25, 26, 27, 28]. Schön stressed the need for theory of practical competence. Based on a study on design behaviour of professionals in practice, he introduced an approach to design, now termed design as '*reflective practice*' [*e.g.* 26, 29, 30, 31]. The main premise of the reflective practice view on design is the idea that a designer subjectively interprets the design task and the situation he or she is in. From this interpretation the designer reflects on the situation to construct a decision about what to do next. This continuous reflection-in-action guides the progression of the design process.

***Overview and awareness:*** Flanagan *et al.* [32] argue that designers greatly benefit from an overview of the product and the process to communicate proactively to their colleagues and understand the information needs and preferred representations of other team members. Awareness has been described as one of the important issues for successful communication and one of the most important components of collaborative work [33]. Fundamentally, awareness of the work of others facilitates communication and is therefore a basis for engaging in any kind of collaborative activity [34].

## 3.2 Unexpected results

Two examples of unexpected correlations are presented below.

#### *3.2.1 Example of an unexpected 'high' correlation*

***'Representation' – 'Autonomy of task execution':*** 'Representation' (referring to the way a product or process is presented throughout the evolving design process, ranging from a bill of materials for example, to a physical prototype) shows a high correlation coefficient with 'autonomy of task execution' (referring to the degree to which a designer can autonomously decide on the way he or she executes a certain task). This result suggests that use and common understanding of a suitable representation of the product in its various stages throughout the design process is connected to the designers' satisfaction with the freedom of and possibility of autonomous execution of tasks. This is a surprising result in that the researchers are not aware of many accounts in the literature which bring the two variables into connection. Rare exemptions noted, such as Eckert *et al.* [35], who suggest that if you do not have clear representations you need to negotiate, as unclear representation hamper carrying your tasks out autonomously.

Given the statistical result, does this mean that increasing understanding of representations increases the possibility of carrying out tasks autonomously within the design process? One could speculate and discuss this result in connection to the argument of 'boundary objects', raised by Star and Griesemer [36] who refer to 'boundary objects' *"(...) as analytic concepts of those scientific objects which both inhabit several interesting social worlds and satisfy the informational requirements of each of them"*. In other words, boundary objects are an entity shared by several different 'communities of practice' [37] but viewed or used differently by them. 'Boundary objects' account for local contingencies and allow for cross-site translations to satisfy different concerns simultaneously [38]. People use 'boundary objects', such as different representations of the product, as means of co-ordination and alignment [39]. The argument here goes that in order to collaborate, one needs common understanding of common 'boundary objects', in our case representations, used at the interface of different collaborating departments in product development.

#### *3.2.2 Example of an unexpected 'moderate high' correlation*

***'Autonomy of task execution' – 'Overview of sequence of tasks in the design process':*** This linkage shows a 'moderate high' correlation coefficient found in our research but not yet supported by literature. It could be hypothesised that the greater the overview, the greater the ability to collaborate, thus a reduced need for clear task separation. Likewise, it could be possible that the greater the overview, the greater the ability of a team to draw clear distinctions between tasks and the greater the ability to assess expertise of colleagues and judge when to contact them and when best not to.

#### *3.2.3 'Separate' variables*

Unexpectedly, 'transparency of decision making', 'common goals and objectives', 'notation', 'hierarchies' and 'availability of information about our company' did not exhibit correlations based on our selection criteria of a correlation coefficient of at least 40% used (see discussion on 'conceptual similarity' in Section 4.2 and future research in Section 6.2).

### 3.3 Literature analysis: The search for a direction of influence

Findings described in the previous section shed light on associations between variables and form the basis for the literature analysis and critical reflection. Given the factors selected in this research project, hypotheses generated above provide the starting point for further research on whether those factors can be depicted as core influences on communication in product design.

Apart from cross-checking whether correlations found in our analyses are confirmed by published studies, the direction of influence is of interest. As elicited correlations are undirected, further evidence is needed in order to determine a possible causal direction. Literature in various disciplines, such as new product development, management science and psychology was consulted as benchmarks and for validation purposes.

#### *3.3.1 Correlations supported by literature*

Table 1 summarises evidence from the literature drawn to support 'moderate high' and 'high' correlations explored in this paper. Evidence for each possible direction has been found. Yet, determination of directions of cause and effect is not conclusive in all cases since in some cases, evidence for both directions could be found.

With regard to the first example of the correlation between ‘collaboration’ and ‘team identity’, references in the literature seem to suggest that ‘team identity’ is one of the drivers of ‘collaboration’ [40, 41, 42]. Thus, a clear direction seems to be apparent. The factor ‘roles and responsibilities’ seems to be another driving factor of ‘collaboration’ [43, 44, 45]. In terms of ‘mutual trust’ and ‘collaboration’, evidence in the literature can be found which supports both directions [46, 47, 48, 49]. Interviewing engineers from 34 medium-sized manufacturing companies about their business relation with customers and suppliers, Bstieler [49] concludes that a higher level of trust is positively related to perceived continuity of collaborative development projects. This supports a bidirectional influence.

Although evidences have been found which indicate trends, results have to be read with a note of caution. Studies have used different research methods and people participating in the studies dealt with different tasks.

*Table 1. Evidence from the literature*

| Factor 1 | | Factor 2 | Reference |
|---|---|---|---|
| Collaboration | ← | Team identity | Collarelli and Boos 1992 [40] |
| | ← | | Vianen and Dreu 2001 [42] |
| | ← | | Badke-Schaub and Frankenberger 1999 [41] |
| | → | | Kuhn and Nelson 2002 [18] |
| Collaboration | ← | Roles and responsibilities | Ahuja *et al.* 2003 [45] |
| | ← | | Perry and Sanderson 1998 [43] |
| | ← | | Moenaert *et al.* 2000 [44] |
| Collaboration | ← | Mutual trust | Krackhardt and Stern 1988 [46] |
| | ↔ | | Bstieler 2006 [49] |
| | ← | | Ng and Chua 2006 [48] |
| | → | | Wong and Cheung 2005 [47] |
| Handling of technical conflicts | ← | Mutual trust | Susman *et al.* 2003 [50] |
| | ← | | Newman 1999 [51] |
| Generation of innovative/ alternative ideas | ← | Mutual trust | Thamhain 2003 [52] |
| Overview of sequence of tasks in the design process | ← | Lessons learned | Ayas 1997 [53] |
| | ← | | Klein *et al.* 2003 [3] |
| Overview of sequence of tasks in the design process | ← | Project reviews | Perry and Sanderson 1998 [43] |
| Autonomy of task execution | ↔ | Representation | Eckert *et al.* 2003 [35] |

### *3.3.2 Suggested correlations not detected in reviewed literature*

Some correlations which were statistically elicited could not be found in the literature:

- Roles and responsibilities ↔ Mutual trust
- Roles and responsibilities ↔ Handling of technical conflicts
- Autonomy of task execution ↔ Overview of sequence of tasks in the design process (see 3.2.2)
- Education/training ↔ Project reviews
- Terminology ↔ Application of corporate vision and values

Several reasons might contribute to this fact. There might be some literature we are not aware of, some literature might have not been appropriate, definitions used in the original data acquisition phase for the individual factors (see Appendix A) might not have concurred with the definitions used in other research projects, or, factors might simply not be linked directly.

### *3.3.3 Potential indirect linkages*

Another aspect why no reference was found for a detected correlation might be that the two respective factors are only linked indirectly. This could apply for example to the correlation between the factors ‘roles and responsibilities’ and ‘mutual trust’ (see Figure 4).

Correlation between ‘collaboration’ and ‘roles and responsibilities’ is supported by three references in the reviewed literature and correlation between the factors ‘collaboration’ and ‘mutual trust’ is supported by four references (see Table 1 and Figure 4). However, no references for the correlation between the factors ‘roles and responsibilities’ and ‘mutual trust’ were found. Within this context, it leads to the assumption that they could be indirectly linked.

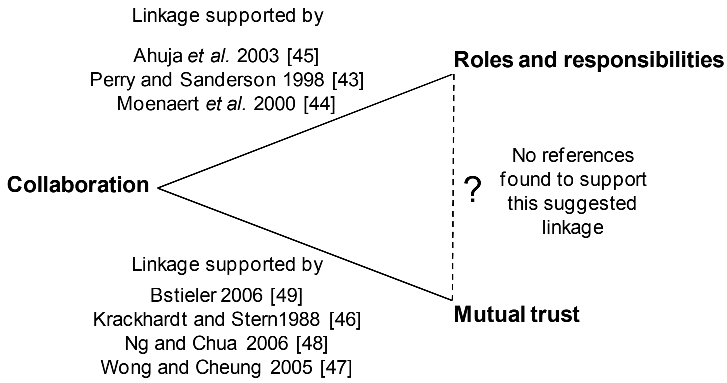


*Figure 4. 'Roles and responsibilities' and 'mutual trust' indirectly linked by 'collaboration'*

## 4 CRITICAL REFLECTION OF RESULTS

Some concerns need to be addressed when statistically exploring correlations between factors influencing communication.

### 4.1 Number of participants

Limitations of our work concern the number of participants in our studies. Further studies should be made to validate the generality of our results. Extension of empirical data might show if the assumed linear behaviour of the correlations can be confirmed, a topic discussed in Section 6.2 (Future Research). A larger number of responses would also allow for consideration of more than 27 factors in future research projects.

### 4.2 Conceptual similarity

Correlations with absolute coefficient values of ≥ 0.40 and statistically significant correlations (min $p \leq 0.05$) were the selection criteria. High correlation between factors may indicate an overlap in the actual factor being evaluated from a conceptual standpoint. Whilst individual analyses may support specific correlations between selected factors, the factor itself may not be conceptually distinguishable. An example could be the linkages between ‘lessons learned’ and ‘overview of sequence of tasks in the design process’ and between ‘lessons learned’ and ‘best practices’ – characterised by a ‘high’ correlation coefficient. They can be viewed as small clusters being tightly related to one another. Often, participants did not explicitly differentiate between the latter two, which basically document experience and knowledge of the process. Equally, although there are more ‘ingredients’ to lessons learned, knowledge about the sequence of process steps was for many participants a major reason for documenting lessons learned.

### 4.3 Frequency of occurrence

We based our analysis on the detected frequency of occurrence and strength of correlation. The criterion ‘frequency of occurrence’ has a powerful influence on later judgements of its value. The issue is to decide which correlations are causally meaningful [54]. Evidence seems to be gathered and understood as converging to support a given correlation. In our case, through statistical and literature analyses, ‘collaboration’ and ‘mutual trust’ indicate thematic centrality. This might indicate a ‘valid’ tendency. It might also indicate a skeletal set of a causal pattern that most people use in similar ways.

## 5 IMPLICATIONS OF RESULTS

Design managers who are confronted with problems in their processes naturally try to understand where these problems are coming from in order to find a solution. However, thinking though these problems can be very difficult and many examples show that symptoms are addressed without an understanding of root causes. This paper proposes patterns of connections between factors that can be a starting point for reflection about a specific design situation and its problems. It is generally easier to recognise connections than to discover them in the first place. It is easy to fall into preferred patterns of explanation and making sense of a situation in familiar terms. The correlations proposed in this paper can challenge these established explanations and might help designers and design managers to see a situation in a new light. Through reframing a problem, patterns might help to overcome fixation. Not all patterns elicited in this paper will be relevant in all situations; however thinking about how the relationship of two factors could influence communication can both provide interesting insight as well as assure managers when certain aspects of their processes are working well.

The example of the 'disappearing' welding spots in Section 1.1 can illustrate how single impacting factors and the correlations can be used to interpret a given situation. There are many factors contributing to the problem of the 'missing' welding spots. Designers are tasked with the interaction with manufacturing engineers. Once the design task is finished the design is handed over to the simulation engineers. The logic of the process, however, could be different. The welding spots might be identified after the analysis of the part, if they do not affect the design. In this case *overview of the sequence of tasks* could be revisited. Alternatively, it might be necessary to bring the simulation engineers into the discussion with the manufacturing engineers and the design engineers earlier in the process, thus requiring a redefinition of the *activity at interfaces with the other party*. As this is a recurring problem, it points to shortcomings in the *lessons learned* procedures in the organisation. If managers are aware of this potential problem ahead of time, they can put better *collaboration* processes in place to avoid this problem. Maybe problems were caused because the *roles and responsibilities* around the placing and recording of welding spots are not clearly defined. The problem might also be indicative of a deeper problem across these different groups, such as *different goals* and assessment criteria, and a *different vision* of the project at large. Managers need to ask themselves where they can come in to improve the situation. Do they want to redefine the process? Do they want to assign clear responsibilities for the problem and leave individuals to take care of the problem? Do they want to invest time and effort to build greater *mutual trust* between the different groups to make them exchange concerns more freely?

The example illustrates that any particular situation can be interpreted in many different ways. While the factors affecting communication imply levers to 'tackle' the situation, they are not universal recipes for improved processes. Each group of designers collaborates with many other groups. Yet, many groups have one or two strong interfaces. For example, the designers in the welding example work very closely with the simulation engineers, but might only have occasional contact with the welding experts. It is crucial for them to work out a relationship of *mutual trust* and *common goals* with the simulation engineers, they might not have the time to put equal effort into their interface with welding experts and prefer to work out a clear definition of responsibilities and treat this issue formally, for example, as a standard question in a review meeting. Nevertheless, increasing transparency into the network of connected factors impacting on communication in product development can reduce uncertainty.

## 6 CONCLUSION AND FUTURE RESEARCH

### 6.1 Conclusions

The overall objective of this paper was to explore interrelations between factors influencing communication in product development emerging from data acquired through empirical studies. A communication grid analysis in five case studies in industry yielded empirical data from engineers and managers scoring their perception on the current status of factors influencing communication. The scores formed the basis for statistical calculations. Research identified interesting associations between factors influencing communication using statistical data analysis techniques. The term association is used as in most cases the nature of connection and direction of influence is inconclusive. Results obtained were brought into conjunction with findings in the literature for validation purposes as well as for an indication of the direction of influence. Correlations identified areas of attention for design management in practice and led to a means of influencing communication directly through uncovering connections between different factors. Factors that possess of a high linking degree, such as 'mutual trust', 'collaboration', 'overview of sequence of tasks in the design process', and 'autonomy of task execution' are portrayed in this paper as core factors influencing communication in product development. Results further show general themes, such as 'reflection' and 'overview' as key to successful communication. Unexpectedly, the factor 'autonomy of task execution' showed statistically significant and a high correlation with, for example, 'representation'. Concluding from the reviewed literature, directions such as the following were suggested: 'team identity' and 'roles and responsibilities' seem to be drivers of 'collaboration'. The analyses provide examples to be compared with results of other research projects, bearing the specific context in mind. Results presented in this paper are seen as explorations into interconnections between factors pertinent to design communication. The premise was that effective communication facilitates an effective design process which contributes towards a good product. As in any other empirical study that collected data from empirical studies with small samples within each study, we cannot claim the generality of our findings before completing similar studies. However, we would expect to obtain analogous results in other projects developing complex systems. This study is descriptive in nature and as such, we avoid drawing explicit normative conclusions.

## 6.2 Future research

Part of the contribution of this paper lies in providing a starting point for further research. For future work we ask ourselves whether the associations identified can be used to generate hypotheses and questions which could be tested in further empirical studies. In order to do that, preliminary questions need to be answered with regard to the nature of correlations found.

### *6.2.1 Exploring the nature of correlations*

We assume that in our network of factors influencing communication there is no centralised controller which means that global behaviour emerges probably as a result of concurrent local actions. Such networks are typically modelled as multiple nodes, each node representing a state variable with a given value. Network dynamics is determined by the nature of the influences between nodes [3]. Therefore we need to ask ourselves, whether the influences are linear or not, and are they symmetric or not? The algorithm used to compute correlations is based on linear influences thus understating possible nonlinear relationships. Linear networks are described as having a single attractor, *i.e.* a single configuration of node states that the network converges towards no matter what the starting point, corresponding to the global optimum. Symmetric networks are ones in which influences between nodes are mutual (*i.e.* if node A influences node B by amount X then the reverse is also true), whilst asymmetric networks (if they have cycles in them) add the complication of having dynamic attractors, which means that the network does not converge on a single configuration of node states but rather cycles indefinitely around a relatively small set of configurations [3].

### *6.2.2 Exploring causal relations of correlations over time*

Reviewing literature is one possibility to receive more information about the chains of cause and effect of the correlations suggested by the performed data analyses. Another approach could be to perform detailed case studies and asking the participants in collaborative design projects directly which factor influences the other factor of a certain linkage. It would also be interesting to see whether exposed correlations can be traced over time. Data acquired for this research project was acquired at a certain point in time. Case studies performed at a certain time could be repeated during different stages of the design process.

### *6.2.3 Incorporation of 'moderate low', 'weak', and 'negative' correlations*

In this paper, only linkages suggested by a 'high' or 'moderate high' correlation coefficient were compared with findings in the literature. In future research projects, 'moderate low' and 'weak' correlations could also be part of the literature review. Also, statistical analyses in this paper are based on positive correlations. Negative correlations were also found, yet not among the decision criteria applied in this paper. They will be basis for further research projects.

## ACKNOWLEDGEMENT

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## APPENDICES

The appendix consists of a table with a glossary of how the factors used in this paper have been defined (Appendix A) and the complete correlation matrix (Appendix B).

### Appendix A: Definition of factors

| Factor | Definition |
|---|---|
| Representation | Degree of understanding and adequacy of the different types of representations of a product (*e.g.* bill of materials, drawings) |
| Notation | Degree of understanding of for example drawing conventions. |
| Terminology | Degree of understanding of specific technical terms used. |
| Do you know what information the other party needs? | Degree of the awareness of the other party's needs and preferences. |
| Availability of information about competitors | How often information about competitors is distributed to the interviewee. |
| Availability of information about our company | How often information about the own company is distributed to the interviewee. |
| Availability of information about procedures | How often information about procedures is distributed to the interviewee. |
| Availability of information about product specifications | How often information about product specifications is distributed to the interviewee. |
| Hierarchies | Understanding how hierarchies can be called upon to achieve clear communication. |
| Usage of procedures | Effort to improve design procedures and the usage of procedures. |
| Roles and responsibilities | Knowledge about someone's own and the other's roles and responsibilities and the use of it while communicating. |
| Activity at interface with the other party | Degree of activity with regards to the interface with the other party. |
| Handling of technical conflicts | How often technical conflicts are addressed and resolved. |
| Transparency of decision making | Transparency of decision making and involvement of the right people in the decision making process. |
| Application of corporate vision and values | Knowledge and application of corporate vision and values. |
| Common goals and objectives | Knowledge and pursuit of common goals and objectives. |
| Mutual trust | Degree of interpersonal trust and effort to create trust within the project team. |
| Best practices | How often 'Best practices' are considered and how 'Best practices' are communicated within the team and to other teams for future task execution. |
| Collaboration | Regularity of collaboration and of the effort to improve collaboration. |
| Team identity | Strength of belonging to the team and degree of reflection how team identity can be strengthened. |
| Project reviews | Degree of quantity and quality of formal and informal reviews to plan actions and to reflect on goals. |
| Lessons learned | How often 'Lessons learned' are considered and how 'Lessons learned' are communicated within the team and to other teams for future task execution. |
| Overview of sequence of tasks in the design process | Degree of everybody's overview of the sequence of tasks in the design process according to their own job description. |
| Autonomy of task execution | Freedom in one's own decisions and task execution in alignment with one's responsibilities and co-ordination with others. |
| Generation of innovative/alternative ideas | How generation of innovative and alternative ideas is supported and rewarded. |
| Education/training | To what degree training and education plans are tailored and executed. |
| Best use of my capabilities | How one's capabilities are realised and utilised. |

## Appendix B: Correlation matrix

Only statistically significant correlation coefficients with an absolute value of ≥ 0.4 were chosen, which accounts for the sparse population of the matrix.

| Symmetric correlation matrix for 'current status' values | | Do you know what information the other party needs | Availability of information about competitors | Availability of information about our company | Availability of information about procedures | Availability of information about product specifications | Hierarchies | Usage of procedures | Roles and responsibilities | Handling of technical conflicts | Decision making | Application of corporate vision and values | Common goals and objectives | Best practices | Autonomy of task execution | Generation of innovative/alternative ideas | Activity at interface with the other party | Mutual trust | Collaboration | Team identity | Project reviews | Lessons learned | Overview of sequence of tasks in the design process | Education/training | Best use of my capabilities | Notation | Terminology | Representation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| Do you know what information the other party needs | 1 | | | | | | | | | | | | | | ,419** N=35 | | | ,413* N=26 | ,405* N=27 | | ,428* N=26 | | | | | | | |
| Availability of information about competitors | 2 | | | | | | | ,400** N=38 | | | | | | | | | | | | | | | | | | | | |
| Availability of information about our company | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Availability of information about procedures | 4 | | | | | | | | | | | | | | | | | | | | | | | ,425* N=28 | | | | |
| Availability of information about product specifications | 5 | | | | | | | ,486** N=38 | ,415** N=38 | ,406** N=38 | | | | | | | | | | | | | | | | | | ,470* N=21 |
| Hierarchies | 6 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Usage of procedures | 7 | | ,400** N=38 | | | ,486** N=38 | | | | | | | | | | | | | | | | | | | | | | |
| Roles and responsibilities | 8 | | | | | ,415** N=38 | | | | ,504** N=38 | | | | | | | | ,520** N=29 | ,512** N=28 | | | | | | | | | |
| Handling of technical conflicts | 9 | | | | | ,406** N=38 | | | ,504** N=38 | | | | | | | | | ,544** N=29 | ,429* N=28 | | | | | | | | | |
| Decision making | 10 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Application of corporate vision and values | 11 | | | | | | | | | | | | | | | | | | | | | | | | | | ,549** N=22 | |
| Common goals and objectives | 12 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Best practices | 13 | | | | | | | | | | | | | | | | | | | | | ,627** N=29 | | | | | | |
| Autonomy of task execution | 14 | ,419** N=35 | | | | | | | | | | | | | | | | | ,497** N=27 | | | | ,505** N=28 | | ,451** N=30 | | | ,653** N=19 |
| Generation of innovative/alternative ideas | 15 | | | | | | | | | | | | | | | | | ,536** N=26 | | | | | | | | | | |
| Activity at interface with the other party | 16 | | | | | | | | | | | | | | | | | | ,524** N=28 | | ,478* N=21 | | | | | | | |
| Mutual trust | 17 | ,413* N=26 | | | | | | | ,520** N=29 | ,544** N=29 | | | | | | ,536** N=26 | | | ,632** N=19 | | | | | ,432* N=19 | | | | |
| Collaboration | 18 | ,405* N=27 | | | | | | | ,512** N=28 | ,429* N=28 | | | | | ,497** N=27 | | ,524** N=28 | ,632** N=19 | | ,519** N=28 | ,491** N=19 | | ,473** N=28 | | | | | |
| Team identity | 19 | | | | | | | | | | | | | | | | | | ,519** N=28 | | | | | | ,407* N=23 | | | |
| Project reviews | 20 | ,428* N=26 | | | | | | | | | | | | | | | ,478* N=21 | | ,491** N=19 | | | | ,556* N=21 | ,567** N=19 | | | | |
| Lessons learned | 21 | | | | | | | | | | | | | ,627** N=29 | | | | | | | | | ,718** N=22 | | | | | |
| Overview of sequence of tasks in the design process | 22 | | | | | | | | | | | | | | ,505** N=28 | | | | ,473** N=28 | | ,556* N=21 | ,718** N=22 | | | | | | |
| Education/training | 23 | | | | ,425* N=28 | | | | | | | | | | | | | ,432* N=19 | | | ,567** N=19 | | | | | | | |
| Best use of my capabilities | 24 | | | | | | | | | | | | | | ,451** N=30 | | | | | ,407* N=23 | | | | | | | | |
| Notation | 25 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Terminology | 26 | | | | | | | | | | ,549** N=22 | | | | | | | | | | | | | | | | | |
| Representation | 27 | | | | | ,470* N=21 | | | | | | | | | ,653** N=19 | | | | | | | | | | | | | |

* significance level; $p < 0.05$
** significance level; $p < 0.01$

'Moderate low' correlation coefficient: White background, black font
'Moderate high' correlation coefficient: Grey background, black font
'High' correlation coefficient: Black background, white font


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