

Communication: Key Factor in Multidisciplinary System Design

**G. Maarten Bonnema, P. Daniel Borches,
Rogier G. Kauw-A-Tjoe, Fred J.A.M. van Houten**

Laboratory of Design, Production and Management, Faculty of Engineering Technology,
University of Twente

P.O. Box 217, NL-7500 AE Enschede, The Netherlands

g.m.bonnema@utwente.nl

Abstract

System design research often looks at ways to model the system that is developing. Many modelling techniques and model representations exist. Another aspect these models can be used for is to enable, facilitate and improve communication among the developers during the process. The young System Design Group at the faculty of Engineering Technology of the University of Twente, the Netherlands, aims at focusing on this communication aspect in system design.

In the paper, a few finished and running projects undertaken in close cooperation with industry are described concisely. From these projects three research themes are derived. These are: creation of high-level models, combining model representations and condense information. The paper ends with plans for future research.

Introduction

Multidisciplinary design is common practice these days. Most products are created

in a joint effort of mechanical engineers, electrical engineers, software engineers and industrial designers. System Engineering is a set of techniques that helps to accomplish that cooperation, see Figure 1.

However, the system engineering techniques alone do not provide the system. Therefore, we will use the term “system design” to indicate the complete process of bringing to existence multidisciplinary systems.

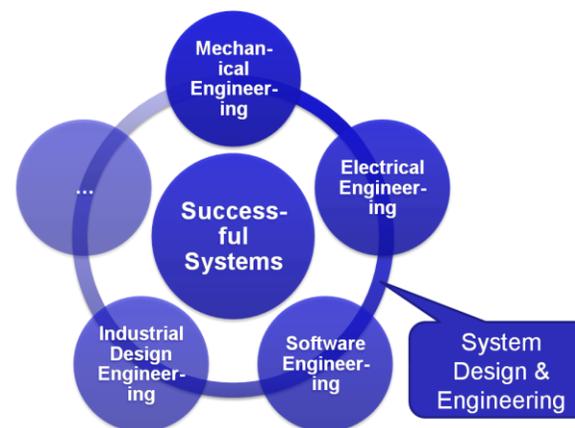


Figure 1: Multidisciplinary cooperation requires special attention.

System design is treated in literature. Several books deal with it (Blanchard and Fabrycky 1998; Hinte and Tooren 2008; INCOSE SEH Working Group 2008; Maier and Rehtin 2000; Sage and Armstrong jr. 2000). Also the present conference is a token of the relevance of the subject. Several interesting articles on the matter have been presented here (Martin and Davidz 2007; Muller 2009; Muller 2005) and elsewhere (Bonnema and Borches 2008; Borches and Bonnema 2008; Martin and Ferris 2008; Sheard and Mostashari 2009). These present a multitude of approaches and tools to facilitate system design. Founded on years of experience by the authors, they contain a wealth of information for the system designer.

The goal of this paper is to show results from the System Design Group that provide hooks for further development and elaboration, and to define the group's research focus. A few interesting research questions are proposed, some of which can be treated by the System Design Group, some should be treated by others or in cooperation with others.

The group resorts under the faculty of Engineering Technology and the Laboratory of Design, Production and Management at the University of Twente. The Laboratory originates from production technology research. Over the past decades the focus has shifted from technology oriented research (the 70's and 80's), via product modelling (90's and 00's) to research on application, usability, concept design and system design (00's). Central in this shift has been that designing gets more multidisciplinary and needs more focus on the ability to solve problems: moving from technology oriented to application oriented research. The System Design Group has emerged from the latter development.

In this paper, we will first look at several past and present projects performed at the System Design Group. This relatively new group already has successfully completed projects in close cooperation with industry.

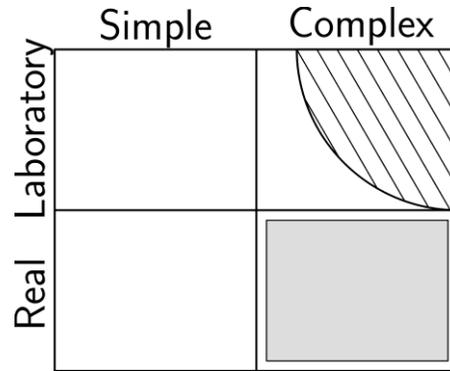


Figure 2: Grid to identify relevant System Design cases.

Based on these, and running projects, the research theme for the group is derived. The links between this theme and the present projects is shown. Also directions for future research are indicated, including specific issues to be investigated.

The paper ends with recommendations for system design research in general, and that of our System Design Group in particular.

Past and Current Projects

Selection of application cases. Defining projects where findings in the area of system design research are applied is not an easy issue. System design research aims at developing tools and methods for design of complex systems. Therefore, testing the applicability of the developed tools and methods requires complex cases. Figure 2 shows possible areas of application, classified using the scales *real* versus *laboratory* and *simple* versus *complex*. The definition of “complex” is open to many interpretations. In this context, we will build upon the use in (Schön and Bennet 1996): “A system is complex in the specific sense that, whenever I make a move, I get results that are not just the ones that I intend. ... Any move has side effects.” It is practically impossible to develop a complex laboratory case as indicated by the hatching in Figure 2. It is clear that to verify the application of developed tools, we have to

resort to real-life cases, indicated by the shading of the bottom-right corner of the grid.

For relevant cases, close cooperation with industry is vital, as also concluded by (Muller 2009) and the Embedded Systems Institute (www.esi.nl). Therefore, in the following project summaries, the industrial partner(s) is (are) mentioned. Also, for future projects, we will always involve a party from industry.

FunKey Architecting. It is found (Bonnema and van Houten 2006) that experienced system designers use a limited number of types of models, where the most important ones are:

- System Budgets to divide performance items over system's components (power budget, error budget etc.);
- Analysis of physical behavior;
- Functional models like Functional Block Diagrams, and Function Structures;
- Specifications and requirements.

In addition to the above, mathematical models are used to determine the system budgets, and sketches are used throughout the process for illustration of solutions and models in general. From this finding and general design literature, it is found that *functions* play a key role in the early phase of system design. However, functions alone are not enough. Connection to performance and the system decomposition, and thus to the interfaces in the system, is needed.

It is proposed to use *key drivers* to represent on the one hand the system's stakeholders' interest, and on the other hand the result of the designer's efforts. Examples are overlay for a wafer stepper, turn-around time for an aircraft, image quality for a medical imaging device. In general a system will have 5-10 key drivers to represent its value for the stakeholders.

The effect of functions on key drivers is investigated using a coupling matrix, see Table 1. Here a coupling matrix for a wafer stepper is shown. The key driver shown is

Table 1: Functions-Key driver scheme for a wafer stepper. A cross indicates there is a contribution from the function to the key driver throughput.

Functions	Key driver Throughput
Load wafer	×
Prealign wafer	×
Wafer to expose chuck	×
Align wafer	×
Expose wafer	×
Maintain focus	
Position stage	×
Unload wafer	×

throughput. Other key drivers are critical dimension; overlay and cost per good die.

As seen from Table 1, nearly all top-level functions contribute to the throughput key driver. The FunKey approach (from FUNctions and KEY drivers) provides direct clues for system improvement using a connection with the Theory of Inventive Problems Solving called TRIZ (Altshuller 1997; Bonnema 2006; Salamatov 1999).

The approach has been applied in a new wafer stepper company: MAPPER Lithography (www.mapperlithography.com), and a company developing and producing waste balers: BOA systems (www.boarecycling.nl). In both cases, several interesting system concepts and system improvements have been found. Moreover, it provided bases for system budgets (MAPPER) and architectures (BOA). Other results include increased insight in, and overview over the system. Also, the ideas and considerations of the system designer could be well conveyed to other engineers involved. Also, FunKey provides means to track technical progress and uncertainties. Overall, FunKey stimulates communication among the developers by

making decisions explicit. See (Alink 2007; Bonnema 2008) for details.

Design for Evolvability/Darwin project.

System requirements change over time; consequently, companies need to systematically evolve their products to cope with those changes. Since developing a system from scratch is time consuming and costly, new systems are often created by evolving an existing system. The knowledge that the company has about the system and the consequences of introducing changes determines its ability to effectively cope with system evolution.

Even in large companies, complex systems are typically poorly documented. The main architecture knowledge resides in the expert's minds, and only part of that knowledge is documented.

An MRI system for example, as developed by our industrial partner Philips Healthcare, requires a multidisciplinary design team. Typically people are specialized in a single discipline, and each discipline uses its own vocabulary. Besides this, all the disciplines have to work together on different aspects of the design. Therefore effective communication across disciplines and departments is essential. The consequences of missing information or misunderstandings can cause serious problems and delays in the development process.

The result of this project is an approach to **collect**, **abstract** and **present** architectural information in a fashion that can be understood and used by a broad set of stakeholders to improve the communication in the project: the A3 architecture overviews.

The main goal of an A3 architecture overview is to have a manageable architectural representation of a system aspect that enables system architects and designers to reason and communicate the consequences of system changes. An architecture overview helps to provide a broad, comprehensive and easy to handle view of the system aspect

under study. It provides a model-based description of the system aspect, consisting of a functional view, a physical view and a quantification of key parameters view. Annotations of design constraints and design decisions are also present. The views are interlinked by allocating functions into the physical view, pointers from one view to another, etc. The A3 summary provides a compact text-based description to support the overview; structured for efficiency. For more information, see (Borches and Bonnema 2009; 2010)

Autonomous Litter-collecting Robot.

Based on a third-year's student project, we have defined together with Stichting Nederland Schoon (Dutch foundation that focuses on a cleaner country), Hako-Werke GmbH (a worldwide leader in outdoor cleaning equipment) and Demcon advanced mechatronics (www.demcon.nl), a project to assist the street cleaners with a cleaning robot. The urban litter collection robot operates as follows. First, the environment is recognised; obstacles and litter are identified. Based on the surroundings, a map is created by means of which the navigation path is determined. Navigation setpoints and the location of the litter are used to control the robot: motion control to drive towards the litter while avoiding obstacles, and collection mechanism control to collect the litter.

FunKey (Bonnema 2008), is used to divide the system into coherent subsystem. This way each created subsystem has an added value, and a possibility to create a unique selling point. However since multiple students work on this robot and all need a clearly defined part to design as a graduation or educational project, some subsystems created with FunKey are divided into smaller parts, adjusted to the level and available time of the students. The resulting subsystems were called modules.

The modules are described by functions and the interaction within and between the functions. The interfaces are described in N² diagrams (INCOSE SEH Working Group 2008), and by specifications of the system and the modules. The infrastructure in the robot is provided by mechanical, electrical and software frameworks; for instance energy supply for all modules by means of batteries.

After having created the system architecture, it is of great importance to ensure the designers keep the architecture in mind at all times. Personal decisions instead of system decisions can have great negative impact on the integration process of modules. This was achieved by regular multidisciplinary discussions on design issues, architecture issues and integration. Finally, during those team meetings, focus has been put on identifying risks and defining appropriate risk mitigation scenarios (INCOSE SEH Working Group 2008).

The next projects will be treated in less detail, because of space limitations.

Design Patterns in Mechatronics. This project is of a more fundamental nature. Yet, it is directed towards industrial application. The research will formulate a design architecture and a framework with which multi domain design processes can be integrated. It aims at the definition of an abstract model layer that connects the various domain specific models and design processes involved. This layer can, in addition to integration, also be used to maintain model consistency and to automate design tasks. It provides views from different domains on the same functionality. Each discipline sees its own familiar representation, while reusing information from other domains.

Industrial partners are vanderlande industries, océ and ASML. They provide a platform for application, but also input to the research itself.

The TeleFLEX project targets the research, design and construction of a tele-manipulation system that controls flexible instruments for common minimal invasive surgery; interventions for which traditional endoluminal surgery, single port surgery and NOTES (Natural Orifice Transluminal Endoscopic Surgery) are suitable techniques.

A tele-manipulation device will generally contain a master interface console and a slave robot. The focus in this project is on the master console, aiming at intuitive and ergonomic control of the instruments with computer support of the motion (multi-Degree of Freedom) and feedback.

Besides new knowledge the project must also result in a technology demonstrator with integrated functionality for the surgeon's cockpit, input controls, feedback devices, signal conversion and data processing. This multidisciplinary project is done in cooperation with another group at the department of Design, Production and Management, other faculties and in close cooperation with surgeons and Demcon advanced mechatronics (www.demcon.nl).

Communication: the key factor

From the project descriptions given above, it is clear that in all projects a multidisciplinary team is involved in the design process. With present day products, there is almost always software, electronics and mechanics involved. Further, ergonomics, business and social sciences may play a role. The question is then how can all these developers be involved, and kept informed in such a manner that the customer's business model is satisfied, and opportunities and use cases are met. The architecture should meet the customer's and developer's needs, see Figure 3 and (Andersson and Penotti 2008).

Common observations from the projects above are that to stimulate multidisciplinary cooperation it is required to:

- Have regular contact between specialists from different disciplines.
- Have regular contact between the developers and stakeholders.
- Enable communication in a common format (or set of formats). This can be on the system level as shown in the FunKey project, the technology and product family level, as seen in the Darwin project, or at more detail levels, as shown in the litter collecting robot project. Diagrams and schemes are one possible format.
- Have appointed (a team of) system engineers/system designers.
- Focus on integration as early as possible. In particular the stepwise integration of two or more disciplines has to be aimed at.
- Involve the hardware as soon as possible; avoid prolonged simulation and optimisation as that may improve potential performance, but does not guarantee basic

operation.

These are supported by the answers from system designers and architects given on a questionnaire in the Darwin project (Borches and Bonnema 2010).

These observations are not all new. The role of the architecture as means to set a baseline in order for all engineers to work towards a set goal is clear to all system engineers. However, the role of the architecture as means for communication among engineers (bottom of Figure 3), among non-engineers (top of Figure 3), and between engineers and non-engineers, requires more attention in future research (Boucher and Houlihan 2008). The architecture should be presented so that both engineers and non-engineers can be involved in the architecture-creation process. Below, these observations will be translated into research themes for the System Design Group.

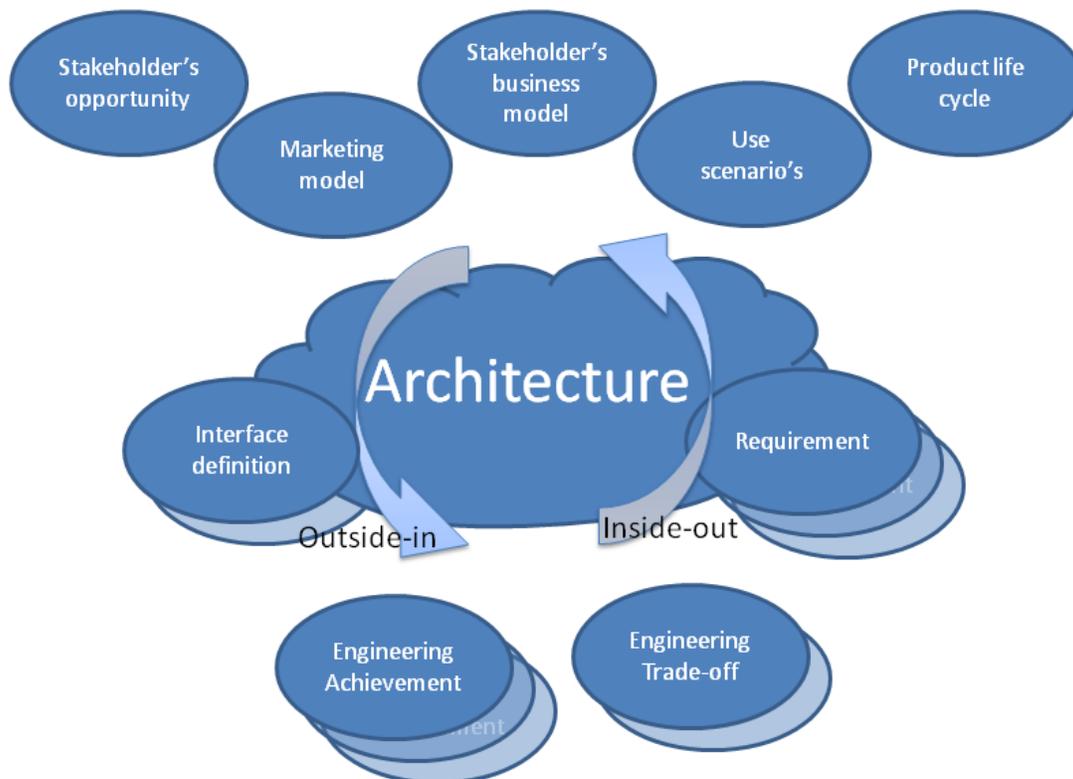


Figure 3: The central role of the architecture as communication means between stakeholders (shown on top) and developers (at bottom).

System Design Group Research Themes

The goal for system design research in general should be to support and assist the system designer in his/her work. It is not wise to take the interesting and creative tasks away from the (system) designer. These provide job satisfaction and motivation. (Csikszentmihayli 1990) describes the state of “flow” when people are challenged enough to avoid boredom and not too much as to create anxiety. This state of flow is related to the skills of the engineers.

Communication is at the core of multidisciplinary cooperation and system design, as seen above. This communication should support both inside-out and outside-in communication, see Figure 3. Here, inside-out communication is from the technology to the application of the system under design (SUD). Thus, what opportunities does the result of the engineer’s effort provide the system buyer? Outside-in communication is about what wishes, demands and requirements does the system buyer pose on the technology.

Proper matching of these two communication streams based on the architecture will result in a more focused system design processes, and avoid engineers aiming for perfect solutions, where a good solution will do. The other way around, the buyer should be aware of technological barriers, risks and limitations. Then the developers and the buyer can express and discuss their limitations, opportunities, and interests and work together towards a good solution that is on time and not too expensive. Thus aiming at optimising profit for the developer, buyer and other stakeholders.

An example (Hinte and Tooren 2008 p.87) is that Airbus salespeople promised customers for the A380 the ability to alter the wiring up to a moment very short before delivery. This, of course, is impossible for such a complex and interlinked system as an aircraft. If the

salespeople would have been more aware of the limitations technology poses, via inside-out communication, this would not have happened. The example also illustrates the fact that communication should not only be stimulated among engineers of different disciplines, but also among engineers and salespeople, engineers and management, etc. Finally, it should be noted that the trigger for a communication can be at the engineer’s side, or the non-engineer’s side (Haveman 2009).

Therefore, we define the following research themes for the System Design Group:

- Create High-level models: Creating a simple to use format (or set of formats) that is understood by all disciplines involved. The format(s) should be able to convey customer interests, technical opportunities and limitations, and result in simpler models that can be used by the more monodisciplinary oriented designers.
- Combine model representations: As each discipline has its own set of frequently used models, it is necessary to investigate a way of connecting these. Goal is that each discipline can look at its own familiar models but use data from other models where needed, without noticing.
- Condense information: We have observed that in contrast to the general idea, expert designers do not use models that are as complete as possible. They use models that are as simple as possible (“but not simpler”, to paraphrase Einstein). The issue is to find the essence of the problem, and describe that as compactly as possible. The process of simplifying the model of the problem is very useful in finding the parameters and processes that determine the actually achieved performance.

In these themes, it is essential to understand the fact that a model is a limited abstraction of reality. Even more so, every observer will have a different view on the system, resulting in different conceptualizations, as shown nicely in (Martin

Table 2: Matrix relating the research themes to the projects treated.

<i>Project</i>	<i>High-level models</i>	<i>Combine models</i>	<i>Condense information</i>
FunKey	××		×
Darwin		×	××
Design patterns	×	××	×
TeleFLEX	×	×	×
Robot	×	×	×

and Ferris 2008). The other way around, when these different conceptualizations are combined, the model will be more complete. Thus, it is essential to make state-transition diagrams and functional block diagrams and power budgets and mechanical sketches and ergonomics mock-ups etc. Together they will provide a more realistic image of the SUD. Relating the different conceptualizations is an issue treated in the second theme.

The first theme tries to create a way to provide the system designer with overview, and the detail designer with context information (Bonnema 2008). The format(s) should be understandable by the customers as well to enable a constant flow of information from the customer to the (system) engineers (outside-in) and vice versa (inside-out).

The last theme aims at avoiding having to read through thick documents, finding inconsistencies and errors. The information should be presented in a concise manner, so that the essence is clear. Correctness should not be corrupted, though.

In Table 2 the projects are related to the themes defined. It is shown that most projects are connected to two themes. There is a focus on one of the themes in the FunKey, Darwin and Design Patterns projects. The TeleFLEX and Litter Robot project use findings of the other projects and act as application cases.

Future

As the group already has good contacts with relevant industry in the Netherlands, the basis for research and evaluation is promising. The number and intensity of partner industries could be improved nationally and internationally.

As the themes have now been defined, it is possible to deepen the research, and to maintain close relations between the projects. This stimulates academic discussions among the researchers. It will also be possible to have more bachelor and master students doing specific researches in companies. Even more, because of the contacts with different industries, a PhD researcher can have a master student apply his research in a different company. This will improve the quality of validation (Martin and Davidz 2007).

Finally, the research results should be used to improve education of mechanical and industrial design engineers, and possibly civil engineers. We will work with people from the Electronics, Math and Computer Science faculty of our university as well, so courses can be improved for those students as well.

In this area, it is interesting to note that systems design and engineering is not formally part of the bachelor program for mechanical engineering, whereas it is part of the program for industrial design engineering. It is our aim to have a basic course on systems design and engineering for industrial design, mechanical and civil engineering within three years. In the master program further deepening and widening will be aimed at.

Further, the use of scenario's, serious gaming and virtual reality appear to be an interesting direction. The cooperation with TxChange at our University is an opportunity. Their effect-based approach to multi-stakeholder problems (Heer 2009) can be one of the means for improved inside-out and outside-in communication.

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Biography

G. Maarten Bonnema is an assistant professor at the Laboratory of Design, Production and Management of the Faculty of Engineering Technology at the University of Twente. He studied Electronic Engineering, and did a two year designer course on Technical Systems. He has worked as a

Systems Engineer at ASML. In 2006 and 2007 he was involved in the design of a wafer stepper at MAPPER lithography (part time). His research involves supporting system designers, conceptual design and mechatronic design. He teaches general design and systems design and is a tutor in student projects.

P. Daniel Borches received his Master's degree in Telecommunication Engineering from the University of Madrid Carlos III in 2004. He has worked several years in companies such as Telefónica R&D and Nokia. From 2006 he is doing his Ph.D. at the University of Twente while working at Philips Healthcare Nederland. The main focus of his research is Systems Engineering and Systems Architecting applied in the industrial sector.

Rogier G. Kauw-A-Tjoe graduated in 2009 for his Master's Degree in Industrial Design Engineering at the University of Twente. He worked at Razzle, his own company, for 6.5 years, designing Human Interfaces, both on paper (corporate identities) and digitally (GUIs). In his Bachelors graduation project, a solar cooker for rural Ethiopia, and in his Masters graduation project, the system design of the urban litter collection robot presented in the paper, human factors were of great importance.

Fred J.A.M. van Houten is head of the Laboratory of Design, Production and Management, and holds the chair on Design Engineering. Prof van Houten has published more than 150 scientific papers. At present he is member of the editorial board of, among others, the CIRP International Journal of Manufacturing Science and Technology, the International Journal of Product Life Cycle Management and the Asian International Journal of Science and Technology. He has been elected as member of the Deutsche Akademie der Technik-wissenschaften (acatech) and he is Vice President of the International Academy for Production Engineering (CIRP). He has presented more than 15 invited keynote papers.