Systematic Design of Connections under Consideration of Assembly and Disassembly related Properties

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In memory of

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Abstract

The subject of this dissertation is the design process of connections, i.e. the selection of existing and the generation of novel connections. Even though connections are responsible for the reliability and the attractiveness as well as for the assembly and disassembly costs of a product, approaches for designing connections are not established yet.

A study of the literature indicates that the available approaches only consider existing connections and do not support the generation of novel ones. Further more, literature indicates that neither these approaches nor the existing schemes for classifying connections sufficiently consider assembly and disassembly processes.

To improve this situation the dissertation has two aims. The first aim is to represent connections such that designers can consider the assembly and disassembly related properties and the corresponding connection characteristics. This leads to the first research question of how the solution space of connections can be represented in order to fulfil this first aim. The second aim is to develop an approach which supports designers in designing connections without the necessity to consider dimensions yet. The related research question is whether the developed approach indeed supports designers.

The first research question is answered by allocating assembly and disassembly related properties to connection characteristics and by representing the solution space of these characteristics. This involves the introduction of ‘connection principles’ that focus on the possible geometries of connections. The results address the first aim in the form of a new connection classification scheme. The results also form the basis for the development of SYCONDE, a systematic approach for designing connections, consisting of a workbook, a set of documentation forms and leaflets with supportive information.

The second research question is addressed by an evaluation of SYCONDE in a design experiment involving ten mechanical engineering students and PhD-students. All were given the same design task to solve. Five participants used SYCONDE (the experimental group) and five did not use SYCONDE (the control group). The experiment showed that, compared to the participants in the control group, the participants in the experimental group performed more activities which were defined as important for designing connections, less frequently repeated some of these activities, considered more solution variants of some connection characteristics, and perceived to a higher level that the solution path is clearly structured and that the considered solution space is large.

Zusammenfassung

Das Thema dieser Dissertation ist der Konstruktionsprozess von Verbindungen, d.h. das. Auswählen existierender und das Generieren neuartiger Verbindungen. Obwohl Verbindungen für die Zuverlässigkeit und Attraktivität sowie für die Montage- und Demontagekosten eines Produkts verantwortlich sind, haben sich Vorgehensweisen zum Konstruieren von Verbindungen bisher nicht etabliert.

Eine Literaturrecherche zeigt, dass die vorhandenen Vorgehensweisen nur existierende Verbindungen betrachten und das Generieren von neuartigen Verbindungen nicht unterstützen. Die Literaturrecherche zeigt ferner, dass weder diese Vorgehensweisen noch die vorhandenen Verbindungsklassifizierungen Montage- und Demontageprozesse ausreichend betrachten.

Um diese Situation zu verbessern, verfolgt die Dissertation zwei Ziele. Das erste Ziel ist, Verbindungen so darzustellen, dass Konstrukteure die Montage- und Demontageeigenschaften und die entsprechenden Verbindungsmerkmale betrachten können. Dies führt zu der ersten Forschungsfrage, wie der Lösungsraum von Verbindungen so dargestellt werden kann, dass dieses erste Ziel erfüllt wird. Das zweite Ziel ist die Entwicklung einer Vorgehensweise die Konstrukteure beim Konstruieren von Verbindungen unterstützt ohne dass dabei schon die Dimensionierung betrachtet werden muss. Hieraus ergibt sich die Forschungsfrage, ob die entwickelte Vorgehensweise Konstrukteure wirklich unterstützt.

Zur Beantwortung der ersten Forschungsfrage werden Montage- und Demontageeigenschaften Verbindungsmerkmalen zugeordnet und der Lösungsraum dieser Verbindungsmerkmale dargestellt. Hierfür werden Verbindungsprinzipe (connection principles) eingeführt, die die möglichen Verbindungsgeometrien betrachten. Mit den Ergebnissen wird das erste Ziel in Form einer neuen Verbindungsklassifizierung umgesetzt. Auf Basis der Ergebnisse wird auch SYCONDE, eine systematische Vorgehensweise zum Konstruieren von Verbindungen, bestehend aus einem Arbeitsheft (workbook), einem Satz Dokumentationsformulare (documentation forms) und einer Blattsammlung mit unterstützender Information (supportive information), entwickelt.

Die zweite Forschungsfrage wird durch eine Evaluierung von SYCONDE anhand eines Konstruktionsexperiments mit zehn Maschinenbaustudenten und Doktoranden beantwortet. Alle erhielten zur Bearbeitung die gleiche Konstruktionsaufgabe. Fünf Teilnehmer verwendeten SYCONDE (Experimentalgruppe) und fünf verwendeten SYCONDE nicht (Kontrollgruppe). Das Experiment zeigte, dass die Teilnehmer der Experimentalgruppe im Vergleich zu den Teilnehmern der Kontrollgruppe mehr der für das Konstruieren von Verbindungen als wichtig definierten Aktivitäten durchführten, einige dieser Aktivitäten seltener wiederholten, mehr Lösungsvarianten für einige Verbindungsmerkmale betrachteten, und in einem höheren Maß den Lösungsweg als klar strukturiert und den betrachteten Lösungsraum als groß empfanden.

Contents

1 Introduction

1.1 Motivation

Connections are vital for any product with two or more components. On the one hand they are responsible for product reliability and thus the attractiveness of the product; on the other hand they determine the processes, efforts and costs for the assembly and disassembly. In the product life cycle, assembly and disassembly processes emerge during production, maintenance, repair, and recycling. Focusing on the production costs, Ehrlenspiel and Bauer mention that more than 50 % of labour time in the metal working industry is used for assembly [Ehrlenspiel et al.-92, p. 180]. The corresponding percentage of costs is even higher [Bauer et al.-91, p. 1] and is numbered between 70 % and 80 % of manufacturing costs. For this reason Bauer considers assembly as the most important industrial production technique [Bauer et al.-91, p. 84]. A survey performed in 2003 by the "Deutscher Verband für Schweißen und verwandte Verfahren e.V. - DVS " (German association for welding and related technologies) states that in Germany 21 billion Euro of added value is achieved through the application of connection techniques representing about 530'000 jobs [VDI nachrichten 39-05]. Surprisingly, approaches for designing suitable connections are not established yet. Projects with car system providers [Arlen–05; Altschwager-05] and discussions with connection experts at Fastener Fair 2005 in Stuttgart/Germany showed that companies generally do not know any of the investigated approaches. The experts also mentioned that "companies usually tend to apply connections established in earlier products than deciding to develop new ones. New connections become necessary when those of earlier products are no longer fulfilling the actual requirements or do not fit the new product. If novel connections are required, these are mostly generated by chance without following any approach." Further, only little literature exists focusing on the design of connections from a holistic point of view. One of the exceptions is Brandon and Kaplan, who recommend to holistically consider the requirements concerning assembly and service life of the products and their components [Brandon & Kaplan-97, p. 12]. For improving connections at equal or decreasing costs, Bauer proposes the consequent application of design methodology and system analysis. He further mentions that a huge range of connections for different applications already exists but that connections are not represented in a clear and comparative manner so that considering all of these and their impacts on the assembly and disassembly processes is hardly possible. This makes selecting the best connection difficult. He concludes that improvement can only be realised through structuring connections [Bauer et al.-91, p. 1, pp. 325]. Ehrlenspiel too states the necessity of supporting the design of connections and to do this as effectively as possible [Ehrlenspiel et al.-92, p. 180]. He perceives as most useful to relate costs of connections to their benefit [Ehrlenspiel-83, p. 175].

The results of this dissertation were partly achieved in the subproject D1 of the collaborative research centre “CRC” 281 “Disassembly Factories for the Recovery of Resources in Product and Material Cycles” [SFB 281 Abschlussbericht-03]. The aim in this subproject was the design of connections enabling disassembly without the need to physically touch the connections. Equipping available connections with actuators for initiating the disassembly process demands too much space and results in complex and expensive products. Hence the focus was on the generation of novel connections. Even though novel connections for supporting different assembly and disassembly processes are continuously introduced, e.g. connections consisting of smart materials in 1999, the fast nut in 2005 and the twin nut in 2007 (Appendix B), general design guidelines for these kinds of connections are not yet defined.

1.2 Aim

The first aim of the research project described in this thesis is the clearly structured representation of connections such that designers can consider the assembly and disassembly related properties and the corresponding characteristics of these connections. Other than the existing connection classification schemes and design approaches focusing on a restricted number of connections, the representation to be realised aims to cover all connections as far as they realise a fixed arrangement under normal ambient conditions in all possible orientations and do not require the supply of energy to hold this arrangement. This restriction is done, because the focus in this thesis is not on connections for individual applications, but on connections which also can be applied to mass products. This leads to the first research question of how the solution space of these connections can be represented holistically. On the basis of the resulting representation the second aim is the development of an approach to support designers in designing connections. This approach is called SYCONDE. Designing connections here includes the selection of existing and the generation of novel connections; dimensioning rules are not considered. Other than the existing design approaches focusing on a restricted number of existing connections, SYCONDE considers of the above mentioned connections the existing and not yet existing. The second research question, whether SYCONDE supports designers, results in the evaluation of SYCONDE.

1.3 Scope

The focus in this thesis is on the assembly and disassembly related properties of connections. While literature provides more or less standardised rules for improving assembly, the improvement of disassembly is not that advanced. For this reason the literature review focuses on disassembly. In contrast to other researchers like Brandon and Kaplan [Brandon & Kaplan-97], assembly and disassembly processes are not analysed and described in detail. They are rather considered in general. According to Pahl et al. [Pahl et al.-07, p. 439], connections have the function to realise a movable or fixed arrangement between components. As already mentioned in Section 1.2, only those connections are considered that realise a fixed arrangement under normal ambient conditions in all possible orientations and that do not require the supply of energy to hold this arrangement. For this reason some physical effects defined by Koller [Koller in Bauer et al.-91, pp. 2-25], i.e. *surface tension*, *gravitation*, *buoyancy*, *aero-/hydrostatics*, *aero-/hydrodynamics*, *electrostatic forces*, *electric magnetism*, *centrifugal and inert force* as well as *impetus* are not considered. Further on, the physical effects *Hooke's law* and *friction*, separately considered by Koller, are summarised as *friction* because if high enough, both physical effects restrict movements through static friction. In the representation of the solution space of connections, *working principles* and *physical effects* are summarised as *working principles*.

1.4 Structure

Chapter 2 deals with the support connections can provide for assembly and disassembly. Connection requirements are described (Section 2.1), rules for supporting assembly and disassembly are presented (Section 2.2) and connection classification schemes are discussed (Section 2.3).

In Chapter 3, existing approaches for the selection and generation of connections are presented (Section 3.1 - 3.5) and discussed (Section 3.6).

In Chapter 4, a new connection classification scheme is presented (Section 4.3). For this, (dis)assembly related properties and corresponding connection characteristics are linked to each other (Section 4.1) and connection principles are introduced (Section 4.2).

Chapter 5 focuses on SYCONDE, an approach to design connections. The requirements on SYCONDE (Section 5.1), a general description of a systematic connection design process (Section 5.2) and the realisation as well as the steps of SYCONDE are described (Section 5.3).

In Chapter 6 the evaluation of SYCONDE is described. The evaluation questions (Section 6.1), the set up (Section 6.2), the analysis (Section 6.3), and the results (Section 6.4) are presented and discussed. Further, the opinions of the participating designers concerning the design process and SYCONDE (Section 6.5) as well as the conclusions (Section 6.6) are given.

Chapter 7 summarises this thesis (Section 7.1), discusses the implementation of SYCONDE in a computer tool (Section 7.2) and ends with some final statements (Section 7.3).

Appendix A consists of an overview of the specific terminology introduced in this thesis.

Appendix B contains a list of connections supporting non- and partially-destructive disassembly.

Appendix C consists of the workbook, the documentation forms (Section C.1) and the supportive information of SYCONDE (Section C.3), and shows their use through an example.

Appendix D presents the design task for the evaluation of SYCONDE (Section D.1), the related questionnaires (Section D.2) and the activities performed by each involved designer while solving the design task (Section D.3).

1.5 Terminology

The most important terms in this thesis are the following. A complete list of terms can be found in Appendix A.

To assemble: To combine at least two components and restrict relative movements between these such that a fixed arrangement results.

To disassemble: To take components apart.

Connection: Technical solution restricting relative movement between two or more components, e.g. upper and lower housing part, and resulting in a fixed arrangement. This can be realised through the components to be assembled only, e.g. snap fit, or through combining these with additives like glue, bolts, nuts etc.

Component: Element with defined geometry and function.

Additives: All elements which are in addition to the components to be assembled necessary for realising a connection, e.g. solders, glues, bolts, nuts.

Fastener: Additive with defined geometry and function (components) which realises the connection without changing its state of aggregation as this is the case for additives like solders and glues.

2 Connections: Requirements, design rules, classifications

Changed assembly and disassembly requirements influence connection requirements (Section 2.1). Several rules and novel connections exist that intend to fulfil these requirements. The rules are discussed in Section 2.2, the connections are listed in Appendix B. Established classification schemes for connections are discussed concerning their ability to represent (dis)assembly related properties (Section 2.3).

2.1 Connection requirements

To investigate the emergence and the fulfilment of connection requirements, the connection issues have to be considered. Connections do not only have to fulfil the function of attaching components. In the last decades several important issues had to be considered. Since the 1970s, this is the increase of efficiency in production. Nowadays the use of connections supporting assembly is state of the art. Since the 1980s, a further issue, namely the reduction of waste and the saving of resources came along. This resulted for many kinds of products in directives of the European Union. In the directive for electrical and electronic equipment is written: “Member States shall encourage the design and production of electrical and electronic equipment which take into account and facilitate dismantling [,i.e. disassembly,] and recovery, in particular the reuse and recycling of WEEE [,i.e. Waste Electrical and Electronic Equipment], their components and materials. In this context, Member States shall take appropriate measures so that producers do not prevent, through specific design features of manufacturing processes, WEEE from being reused, unless such specific design features or manufacturing processes present overriding advantages, for example, with regard to the protection of the environment and/or safety requirements” [Directive 2002/96/EC].

Two kinds of recycling are generally distinguished, product recycling, i.e. the reuse of products or components of these under maintenance of their function, and material recycling, i.e. the reuse of material of products or components of these. Components to be materially recycled can be damaged; those to be product recycled should not. Hence, in accordance with the intended recycling process, connections have to fulfil different requirements concerning their disassembly related properties.

Focusing on all these issues, the fulfilment of function and the provision of specific assembly and disassembly related properties makes the design of connections a complex process.

2.2 Rules for supporting assembly and disassembly

In the following, the rules for supporting assembly (Section 2.2.1) and disassembly (Section 2.2.2) are considered. The focus is on design rules supporting disassembly.

2.2.1 Support of assembly

Since the 1970s efficiency in production increased considerably. This was realised on the one hand through the introduction of automation in production and on the other hand through the establishment of novel connection techniques, e.g. snap fit connections, [Wünsche & Meyer-Eschenbach-06, pp. 1175; Schlüter-94; Roth-96, pp. 7-10]. In the following only few contributions are presented because the support of assembly processes is established and rules are well summarised amongst others by Boothroyd and Dewhurst [Boothroyd & Dewhurst-87].

Schmaus and Kahmeyer [Schmaus & Kahmeyer-92, p. 280] present the following basic design rules for supporting assembly:

- to use as few components as possible;
- to provide connections assembled through linear movements;
- to provide connections assembled vertically from the top;
- to provide sufficient space for the assembly process;
- to provide accessibility from all directions;
- to prevent limp (biegeschlaffe) components;
- to integrate necessary additives, e.g. integrated snap fit connection;
- to provide the possibility of catching and identifying the components;
- to provide sub-assemblies which can be pre-mounted;
- to provide design details supporting assembly, e.g. mounting holes with chamfers.

Boothroyd and Alting [Boothroyd & Alting-92] as well as Boothroyd et al. [Boothroyd et al.–02] mention that the simplification of the product structure, i.e. the elimination of components, for both manual and automated assembly processes leads to substantial savings in costs for assembly and components, even if the remaining components are more complex. Boothroyd et al. [Boothroyd et al.–02, pp. 203] conclude: “For automated processes this [the simplification of the product structure] is even more important when the elimination of one component eliminates a complete station on an assembly machine including the parts feeder, the special workhead, and the associated portion of the transfer device”. Boothroyd and Dewhurst [Boothroyd & Dewhurst–87, pp 1-6] point at the following characteristics the product and the assembly process should have for realising a cost efficient automation:

- number of components in the considered assembly is low;
- product variety, i.e. relationship between total available components and those necessary for one product variant, is low;

- annual production, i.e. number of assemblies per year, is high.

2.2.2 Support of disassembly

The focus of this thesis is on disassembly because its support is less well established than the support of assembly. First, investigated classifications of disassembly processes as well as rules and approaches for supporting disassembly are described. Then, disassembly processes are newly classified and resulting design rules are presented.

Classifications of disassembly processes

The following classifications focus on the condition of the disassembled components.

VDI 2243 [VDI 2243-93], Brinkmann et al. [Brinkmann et al.-94], Milberg and Dieterle [Milberg & Dieterle-93], Hartmann and Lehmann [Hartmann & Lehmann-93], Feldmann and Hopperdietzel [Feldmann & Hopperdietzel-93] classify disassembly processes in:

- fully-destructive, i.e. both the components and the additives are damaged, reassembly is not possible any more;
- partially-destructive, i.e. only the additives are damaged, reassembly is possible when these are replaced;
- non-destructive, i.e. neither the components, nor the additives are damaged, reassembly is possible.

Other than the authors above, Lambert and Gupta [Lambert & Gupta-05, pp. 15-16] focus only on partially- and non-destructive disassembly processes, not on those causing substantial destruction of the components. They classify non-destructive disassembly processes into:

- reversible and
- semireversible.

A disassembly process is reversible if it equals the reversed assembly process, e.g. the disassembly process of a screw. A semireversible disassembly process is mostly more complex than the corresponding assembly process, e.g. the disassembly process of a snap fit.

In this dissertation disassembly is a process that obtains at least the components in non-damaged condition. Fully-destructive disassembly processes are not further considered. For this reason the classification of Lambert and Gupta is more suitable here.

The classification of Härtwig [Härtwig-05; Härtwig in Sfb 281 Abschlussbericht-03, p. 240] focuses on disassembly tools and their level of automation. Basing on Spur's classification of assembly processes [Spur-87], Härtwig classifies disassembly processes in:

- manual disassembly without tool;
- manual disassembly with manual tool;
- manual disassembly with mechanised tool;
- automated disassembly.

The types of disassembly processes determine the most suitable connection, and hence the process of selecting and generating connections.

Rules and approaches for supporting disassembly

In the following, several rules and approaches for supporting disassembly are described. They focus on the reduction of connections and the necessary disassembly processes. Also constraints and prerequisites for a cost efficient automation of disassembly processes are considered and approaches for realising this are presented.

For saving assembly costs, the simplification of the product structure is proposed (Section 2.2.1). Relating this to disassembly, various authors [Kugler et al.-92, p. 41; Barrenscheen-92, p. 119; Beitz et al.-92, p. 146; Milberg et al.-92, p. 224; Schmaus & Kahmeyer-92, p. 282; Bernhart-92, p. 305; Witte & Stolze-92, p. 365] propose the reduction of the number of connections for decreasing disassembly efforts and times. Schmaus and Kahmeyer [Schmaus & Kahmeyer-92, p. 282] suggest centralised connections instead of many connections spread around. Milberg et al. [Milberg et al.-92, pp. 222] propose to disassemble only those components to be product-recycled and to shred the remaining ones so that fewer connections than assembled must be disassembled.

Connections to be disassembled are to be standardised such that few different tools and processes are necessary [Schmaus & Kahmeyer-92, p. 282; Witte & Stolze-92, p. 365; Bernhart-92, p. 305]. Movements required for disassembly should be simple and linear [Warnecke & Schraft-84; Andreasen et al.-85; Bäßler-88; Dieterle-95; Ebach et al.-92, p. 60; Barrenscheen-92, p. 119; Schmaus & Kahmeyer-92, p. 280]. Connections should also be well detectable [Bernhart-92, p. 305] and accessible [Witte & Stolze-92, p. 365, Bernhart-92, p. 305, Milberg et al.-92, pp. 222].

For cost efficient automation of disassembly processes, the characteristics of the product and its disassembly process should be analogue to those described in Section 2.2.1 for the cost efficient automation of assembly processes, i.e. low number of components in the considered assembly, low product variety and high annual number of products to be disassembled. Dieterle [Dieterle-95], Barg [Barg-91] as well as Schmaus and Kahmayer [Schmaus & Kahmayer-92] mention that this is more difficult to achieve for disassembly than for assembly, because the number of identical products simultaneously ready for disassembly and available at one place is low. Furthermore, even if the products are identical, they have their individual life cycles [Dieterle-95, p.85; Barg-91, Schmaus & Kahmayer-92, p. 288] resulting in varying disassembly related properties, e.g. varying disassembly forces due to varying levels of corrosion at the connections [Dieterle-95, p.85; Barg-91; Schmaus & Kahmayer-92, p. 288; Duflou et al.-05, p. 2; Milberg et al.-92, pp. 222; Bernhart-92, p. 305].

As an approach for cost-efficiently increasing the level of automation, Schmaus and Kahmeyer developed a flexible disassembly unit with several robots and disassembly tools. The benefit is that varying kinds of products can be processed on one facility [Schmaus & Kahmeyer-92, p. 288-294]. However, the necessary processes must be defined individually for each kind of product.

Since the end of the 90s, new approaches for automating disassembly came up, namely "Active Disassembly through Smart Materials" (ADSM) [Chiodo-99a] and "One-to-many disassembly processes" [Duflou et al.-05, p. 2]. These approaches are based on novel connections enabling disassembly without contacting the connections (Appendix B), i.e. no one connection needs to be accessed directly and no tool positioned. The benefits of these approaches are disassembly facilities with low complexity, identical disassembly processes without requiring any adaptation to the products, and the possibility of simultaneously disassembling multiple connections.

The before mentioned rules and approaches for supporting disassembly only focus on disassembly processes requiring contact with the connection and thus neglect the newer approaches like ADSM.

New classification of disassembly processes and resulting design rules

For enabling the formulation of general rules for the design of disassembly supporting connections, a new classification of disassembly processes is proposed. This classification is slightly geared to the above mentioned classification of Härtwig. However, it focuses on the necessity of contacting the connection for disassembly and thus considers also newer approaches like ADSM. This results in the following kinds of disassembly processes:

- Contact-based disassembly processes, i.e. contact with the connection or the assembled components is required because disassembly is initiated through movements and forces, e.g. the rotation of bolt and nut relatively to each other or the movement of the hook of a snap fit connection.
- Contactless disassembly processes, i.e. contact with the connection or the assembled components is not necessary. Disassembly is not initiated through movement and force but through triggers not requiring any alignment with the connection or the connected components. These triggers are further divided according to their transmissibility in:
  - Pathway triggers, i.e. triggers are transmitted through a specific pathway, e.g. electric current to be supplied by an electric conductor.
  - Non-pathway triggers, i.e. triggers are transmitted through the atmosphere not requiring any specific pathway, e.g. alternating magnetic field.

In the following, some application fields of these disassembly processes are given and rules for designing connections supporting these processes are presented.

Contact-based disassembly processes are suitable for the individual treatment of products, e.g. service, maintenance and repair as well as product recycling in small lots. These connections should be easily accessible and should enable disassembly with few and standardised tools in short time. The established and already mentioned design rules are valid.

Contactless disassembly processes can be applied to different products as long as these contain connections supporting these processes. This kind of disassembly process is a promising option for cost-efficiently automating disassembly because not the number of identical products is relevant for achieving cost-efficiency but the number of products with similar connections. Beneficial for this kind of disassembly would be, if connections and triggers and thus also disassembly facilities were standardised. Safety against unintended disassembly must be ensured. It is useful to also enable contact-based disassembly in case these connections must be disassembled outside of the disassembly facility for service, maintenance or other reasons. The costs of these connections should be similar to those of available ones. Necessary pathways should be built in during production.

Three connections were prototypically developed supporting the above disassembly processes, namely the *removable bolt head I*, supporting contact-based disassembly, as well as the *removable bolt head II* and the *hose clip with melting element*, supporting contactless disassembly with pathway trigger (Appendix B).

2.3 Connection classification schemes

The investigated connection classification schemes and their classification criteria are listed in Table 2-1 and were analysed concerning their ability of determining the (dis)assembly processes. However, not all of these schemes are relevant for this thesis. For example, the classification of connections according to disassembly related properties, e.g. *permanent*, *serviceable* and *occasionally reopenable* [Rotheiser-04, p. 38], do not in any way describe the (dis)assembly processes and for this reason the corresponding schemes are not considered here. The (dis)assembly processes can be derived from the working principle/physical effect and the geometrical characteristics. Hence, the most relevant classification schemes with these classification criteria are discussed below and are marked in grey in the first column of Table 2-1.

Table 2-1: Investigated classification schemes and the criteria considered by the authors

Reference:	**Classification criteria:**				
	Working principle/ physical effect	**Geometrical characteris-tics**	**Assembly related properties**	**Disassembly related properties**	**Necessity of additives**
Koller [Koller in Bauer et al.-91, pp. 2-25]	■	■			
Roth [-96, p. 13]	■				■
VDI 2232 [-04, p. 2]	■				■
Pahl et al. [-07, pp. 439]	■				
Bley et al. [-92, pp. 270-273]	■			■	
Jentschura [Jentschura in Sfb 281 Abschlussbericht-97, p. 61]	■	■			■
Ewald [-72]	■		■	■	■
Steinhilper & Röper [-86, p. 1]	■				
Brandon & Kaplan [-97, pp. 5-9]	■		■		
LeBacq et al [-02, p. 408]	■		■		
Suhr [-96, p. 97]	■	■	■	■	
Klein [-94, pp. 46]		■			
DIN 8593-0 [-03]	■			■	
Ehrlenspiel [-95, p. 387]	■			■	
Esebeck & Schmidt-Kretschmer [-94]	■		■	■	
Gao [-83]	■				
Hildebrand [-83]			■	■	
Lindemann et al. [-07, slide 25]	■				
Richter et. al. [-59]	■			■	■
Rotheiser [-04, p. 38]				■	

Koller lists about 14 types of physical effects suitable for restricting movements between components (Section 3.2). However, not all of these effects can be used for realising the connections considered in this thesis (Section 1.3). Roth also focuses on physical effects. Other than Koller, he explains these by means of available connections and clusters the physical effects in accordance with their cause in the following *kinds of locking* (Schlussarten) [Roth-96, pp. 13; VDI 2232-04, p. 2]:

- *material locking*: caused through material and the physical effect 'cohesion', i.e. intermolecular attraction between components of identical material. Example of a connection: Welded connection between components of identical (!) material.
- *form locking*: caused through the geometrical form and the physical effect that movements of separate components are restricted if their geometries are meshed. Example of a connection: Snap fit.
- *force locking:* caused through different kinds of forces resulting from a variety of physical effects, e.g. elasticity; gravitation; inertia; magnetism; adhesion; friction. Example of a connection: Soldered connection.

Roth's clustering of physical effects into kinds of locking is in some places confusing because connections realised through identical locking technologies are allocated to different kinds of locking. For example, a welded connection between components of identical material is allocated to material locking while a welded connection between components of different materials is allocated to force locking. Roth explains this with the adhesive forces between components of different materials. For this reason he also allocates soldering and brazing to force locking. However, cohesion can be traced back to molecular forces and for this reason Roth's allocation is not unambiguous. Pahl et al. and Bley et al. define categories nearly identical to Roth. They classify connections into *material*, *form* and *force connections* [Pahl et al.-07, pp. 439; Bley et al.-92, pp. 270-273]. However, the difference to Roth is that they also allocate those connections basing on adhesion, e.g. welded, soldered, brazed, glued connections between components of different materials, to material connections.

Many connections are realised through both form and force locking, e.g. rivets and screws. These connections cannot clearly be allocated with the before described classifications. For these, Jentschura, Ewald, Steinhilper and Röper, and Bley et al. added the category *form and force connections* [Jentschura in Sfb 281 Abschlussbericht-97, p. 61; Ewald-72; Steinhilper & Röper-86, p. 1; Bley et al.-92, pp. 270-273].

The classification of Brandon and Kaplan distinguishes between *mechanical*, *chemical* and *physical connections* [Brandon & Kaplan-97, pp. 5-9]. However, many connections cannot be clearly allocated using the last two categories because they belong to both chemical and physical connections, e.g. soldered and glued connections. The category *mechanical connections* similar defined as *mechanical fastening* by LeBacq et al. [LeBacq et al.-02, p. 408] who further used the categories *welding* and *adhesives*, clearly allocates those connections to categories which are basing on form or on both form and force.

While the (dis)assembly processes of connections not realised through form or both form and force, i.e. non-mechanical connections, can generally be determined, this is not possible for those connections locked through form or both form and force, i.e. mechanical connections. The general determination of (dis)assembly processes of non-mechanical connections is possible, because these connections are always initiated directly at the interfaces of the components to be assembled and thus the geometry of non-mechanical connections and the related (dis)assembly processes can be considered uniformly. For example, assembling a welded or soldered connection requires the combination of the component to be assembled, the provision of defined temperatures and probably some specific additional material further specified through the locking method, while the disassembly of such connection requires the provision of defined temperatures and the removal of the components. The general determination of (dis)assembly processes of mechanical connections is in most cases not possible, because these connections are mostly not initiated directly at the interfaces of the components to be assembled, but base on the interaction of complex geometries, e.g. undercuts, fasteners and mechanics. The only indication for determining the (dis)assembly processes of these connections are the movements that are necessary, but due to the fact that the types, number and forces of these movements strongly vary with the geometrical characteristics of the specific connection, the (dis)assembly process cannot generally be determined, e.g. (dis)assembly movements of a screw or a cantilever snap fit. Thus, for enabling the determination of (dis)assembly processes of mechanical connections, the following information is also necessary:

- interface geometries of the components to be assembled;
- geometry of fasteners, if used;
- geometry of the connection, i.e. geometry of the assembled components and fasteners.

Koller [Koller-84, pp. 177-180] classifies variables of the component geometry and uses these for varying the geometry of the components and the resulting connection. However, classifying the geometry of components through their variables is too detailed and does not result in a classification of component geometries. Suhr and Klein classify the interface geometries of the component to be assembled in *plane* and *bent* [Suhr-96, p. 97; Klein-94, pp. 46]. The scheme of Jentschura classifies the geometry of connections in the categories *piercing*; *entangling* and *coupling* [Jentschura in Sfb 281 Abschlussbericht-97, p. 61]. These categories are a good approach but they are still too general for adequately determining the (dis)assembly processes.

The adequate determination of the (dis)assembly processes requires for mechanically locked connections beside the working principle/physical effect also the geometrical characteristics of the connection. Because such a classification could not be found, a new scheme was realised in Chapter 4. In this scheme both working principles and geometrical characteristics are considered.

3 Connections: Selection and generation approaches

Investigation of literature showed that only few approaches exist that focus on the selection or generation and thus on the design of connections. In the following these are shortly described by author in Sections 3.1 - 3.5 and discussed in Section 3.6.

3.1 Roth

Roth developed *matrices* for the general representation of free and restricted movements between components (Section 3.1.1). His *design catalogues* (Section 3.1.2) classify connections according to determined criteria and should support the designer in selecting suitable ones. For the generation of novel connections, Roth proposes a *morphological chart* (Section 3.1.3).

3.1.1 Matrices

For a clear and standardised indication of free and restricted movements, i.e. degree of freedom, between two components *a* and *b*, Roth developed three different kinds of matrices, the *locking matrix* (Schluss-Matrix) $S_{a,b}$, the *kind of locking matrix* (Schlussarten-Matrix) $S^A{}_{a,b}$ and the *digitised kind of locking matrix* (Digitalisierte Schlussarten-Matrix) $S^D{}_{a,b}$ [Roth-96, p. 135]. The locking matrix and the kind of locking matrix are explained in the following. Information about the digitised kind of locking matrix can be obtained in Roth [Roth-96, pp. 127]. The locking matrix $S_{a,b}$ [Roth-96, pp.120] focuses only on the degree of freedom resulting from combining the geometry of the components a and b, i.e. form locking [Roth-96, p. 135]. Free movements between the components are indicated by “0”, restricted movements by “1”.

Figure 3-1 illustrates in four sections the preparation of a locking matrix. In Section 1, identifiers and directions of translatory and rotatory movement vectors are defined in a 3D-orthogonal system. In Section 2, these vectors are allocated to the cells in the locking matrix $S_{a,b}$. Sections 3 and 4 show exemplarily how the degree of freedom of the combined components a and b (Section 3) is represented in the locking matrix $S_{a,b}$ (Section 4).

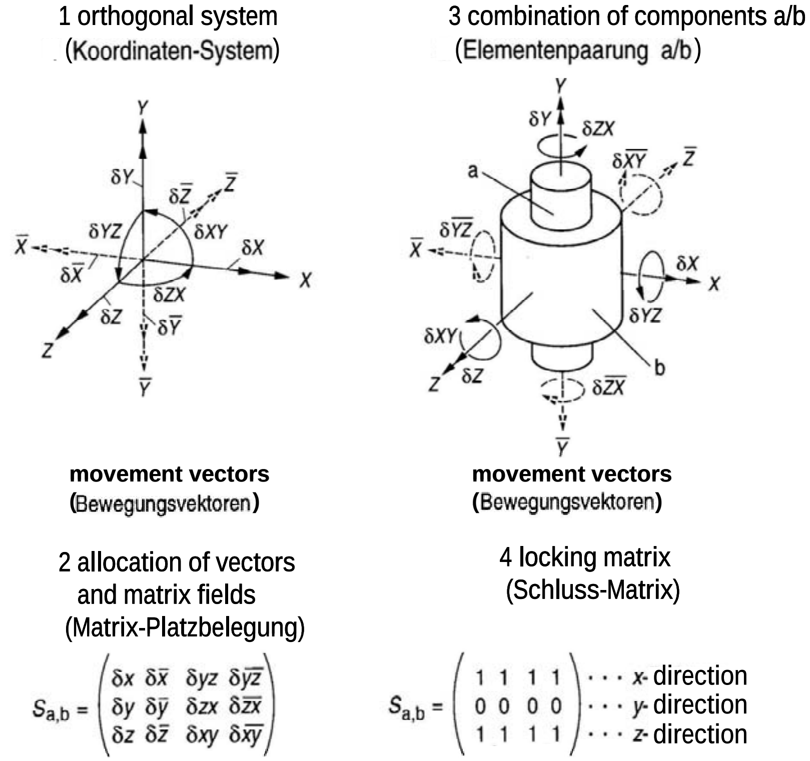
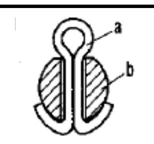
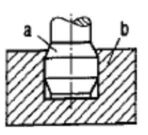
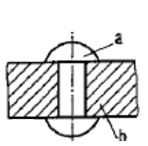


Figure 3-1: Preparation of a locking matrix $S_{a,b}$ [Roth-96, pp.120] (English translation added)

In the *kind of locking matrix* $S^A_{a,b}$ restricted movements are not indicated by "1" any more but by the kind of locking causing the restriction. Figure 3-2 shows locking matrices $S_{a,b}$ and kind of locking matrices $S^A_{a,b}$ of some connections.

connection		$S_{a,b}$	$S^A_{a,b}$
	**cotter-pin**	$\begin{pmatrix}1&1&1&1\\1&1&1&1\\1&1&1&1\end{pmatrix}$	$\begin{pmatrix}f&f&f&f\\f&f&f&f\\f&f&f&f\end{pmatrix}^A$
	**snap fit**	$\begin{pmatrix}1&1&1&1\\1&1&0&0\\1&1&1&1\end{pmatrix}$	$\begin{pmatrix}f&f&E&E\\E&E&r&r\\f&f&E&E\end{pmatrix}^A$
	**rivet**	$\begin{pmatrix}1&1&1&1\\1&1&0&0\\1&1&1&1\end{pmatrix}$	$\begin{pmatrix}f&f&E_f&E_f\\E_f&E_f&r&r\\f&f&E_f&E_f\end{pmatrix}^A$

Abbreviations of the kinds of locking defined by Roth [Roth-96, p. 117]:
s: material locking;
f: form locking;
force locking is further split into:
E_f: stiff force locking through elastic deformation (elastisch "steif");
E: flexible force locking through elastic deformation (elastisch "nachgiebig");
r: friction force locking (reibschlüssig);
g: gravitation force locking (schwereschlüssig);
m: magnetic force locking (magnetschlüssig).

Figure 3-2: Locking ($S_{a,b}$) and kind of locking ($S^A_{a,b}$) matrices [Roth-96, p. 19] (English translation added)

3.1.2 Design catalogues

Design catalogues are schemes classifying existing solution variants according to different criteria and intended to support the designer in selecting the best solution variant. Through the continuous variation of the characteristics related to these criteria, the generation of novel solution variants is possible. With catalogues of different concretisation level, different design stages are considered. Roth classifies connections and supports their selection through design catalogues but he does not describe the generation process of connections.

As can be seen in the first row of Figure 3-3, Roth [Roth-00, pp. 12] structures design catalogues in three sections and an appendix:

- *classification section* (Gliederungsteil), assuring completeness and avoiding overlapping description of the solution variants;
- *main section* (Hauptteil), explaining the solution variants;
- *access section* (Zugriffsteil), supporting the selection of solution variants;
- *appendix* (Anhang) containing further information about the solution variants like examples of their application, existing variants, references to further catalogues, standards, etc.

For the early design stage with a low concretisation level Roth provides a catalogue with kinds of locking [Roth-00, pp. 14]. He classifies and describes the kinds of locking in the classification and main sections. The selection of suitable kinds of locking is supported by the access section. Having determined suitable kinds of locking, the corresponding appendix refers to more specific catalogues. An example of such catalogues is the design catalogue of rivets (Figure 3-3). From this catalogue the designer can select suitable riveted connections.

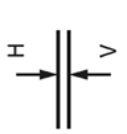
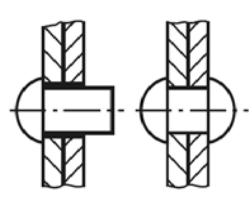
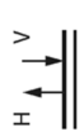
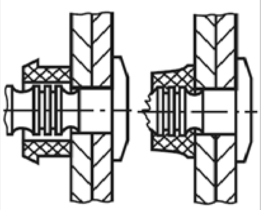
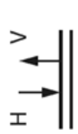
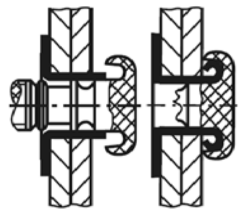
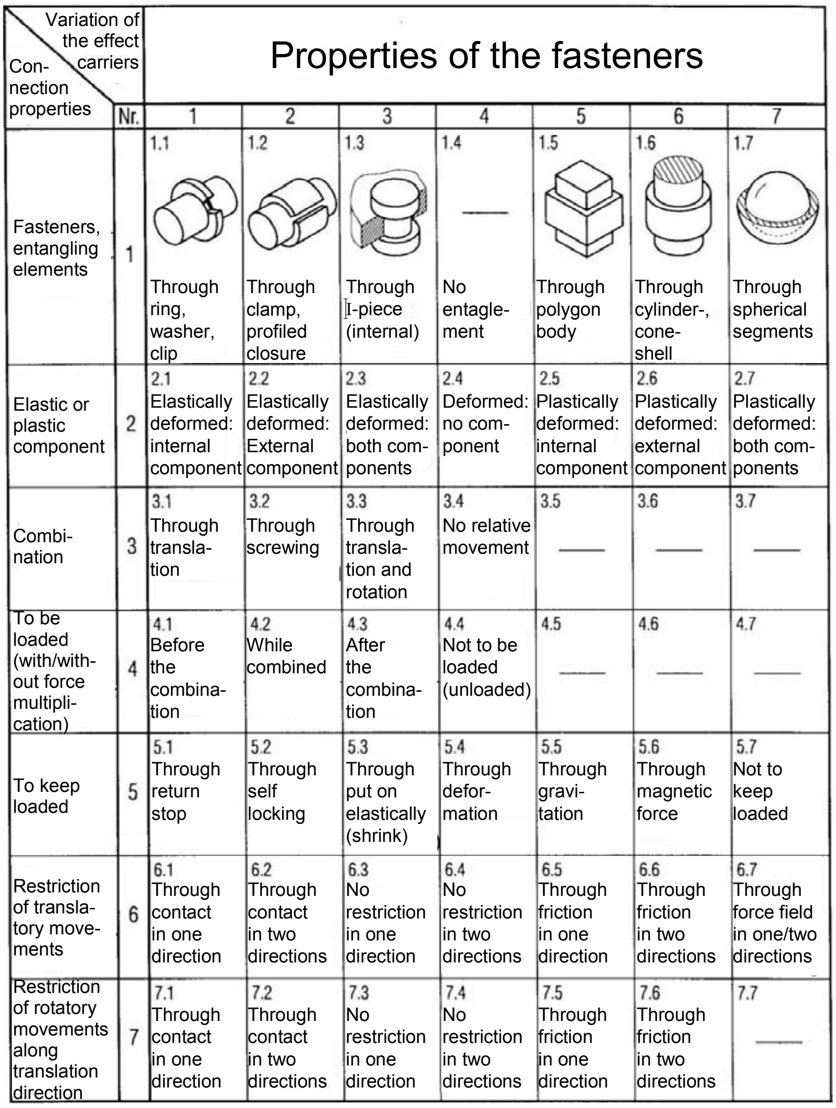
Classification section			Main section			Access section								Appendix
Access to rivet position	Kind of rivetting	Principle of rivetting H = holding force V = deformation force	Identifier	Example	Nr.	Shear strength	Tensile strength	Nominal diameter of rivet [mm]	Self-punching	Tool for rivetting	Additional function	Clamping area [mm]		Remarks/ variants
1	2	3	1	2		1	2	3	4	5	6	7		1
From both sides	Indirect		Rivet		1	Very low to very high		0.7 - 40	To some extent	Attaching machine; rivet hammer, holding-up hammer,	Decorative cap	0.8 - 136		Variants: solid rivet, tubular/hollow rivet, semi-tubular rivet, hollow rivet with cap, mainly standard parts; various specific types available
			Rivet with steel collar		2	Medium to high		5.0 - 10	No	Manual operated tools; tools operated through compressed air	—	0.8 - 44.5		—
			Stud rivet		3	High	Medium	10	No	Hydraulic and peumatic operated attaching tools	—	14.3 - 33.4		—

Figure 3-3: Extract from catalogue with specific connections, here rivets [VDI 2232–04, p. 33] (English translation added)

3.1.3 Morphological chart

For the generation of novel connections, Roth proposes his morphological chart (Figure 3-4). In this chart connection properties should be listed in the first column while the corresponding rows should contain properties of the fasteners that relate to the particular connection properties. However, the entries in this chart are not completely clear because the first column rather contains effect carriers like ‘fasteners and entangling elements’ and ‘elastic or plastic component’ (row 1 and 2 in Figure 3-4), as well as functions like ‘to be loaded with/without force multiplication’ (row 4 in Figure 3-4). The corresponding rows rather describe working principles, e.g. restriction of translatory movements can be realised ‘through contacting these in two directions’ (cell 6.2 in Figure 3-4). According to Roth, novel connections should be generated through selecting from his morphological chart (Figure 3-4), row by row, possible solution variants for each of the movement vectors X, Y, Z illustrated in Figure 3-1, Section 1, and through combining these.



Variation of the effect carriers / Connection properties	Nr.	1	2	3	4	5	6	7
		Properties of the fasteners						
Fasteners, entangling elements	1	1.1 Through ring, washer, clip	1.2 Through clamp, profiled closure	1.3 Through I-piece (internal)	1.4 No entagle-ment	1.5 Through polygon body	1.6 Through cylinder-, cone-shell	1.7 Through spherical segments
Elastic or plastic component	2	2.1 Elastically deformed: internal component	2.2 Elastically deformed: External component	2.3 Elastically deformed: both com-ponents	2.4 Deformed: no com-ponent	2.5 Plastically deformed: internal component	2.6 Plastically deformed: external component	2.7 Plastically deformed: both com-ponents
Combi-nation	3	3.1 Through transla-tion	3.2 Through screwing	3.3 Through transla-tion and rotation	3.4 No relative movement	3.5 —	3.6 —	3.7 —
To be loaded (with/with-out force multipli-cation)	4	4.1 Before the combina-tion	4.2 While combined	4.3 After the combina-tion	4.4 Not to be loaded (unloaded)	4.5 —	4.6 —	4.7 —
To keep loaded	5	5.1 Through return stop	5.2 Through self locking	5.3 Through put on elastically (shrink)	5.4 Through defor-mation	5.5 Through gravi-tation	5.6 Through magnetic force	5.7 Not to keep loaded
Restriction of transla-tory move-ments	6	6.1 Through contact in one direction	6.2 Through contact in two directions	6.3 No restriction in one direction	6.4 No restriction in two directions	6.5 Through friction in one direction	6.6 Through friction in two directions	6.7 Through force field in one/two directions
Restriction of rotatory movements along translation direction	7	7.1 Through contact in one direction	7.2 Through contact in two directions	7.3 No restriction in one direction	7.4 No restriction in two directions	7.5 Through friction in one direction	7.6 Through friction in two directions	7.7 —

Figure 3-4: Morphological chart for the generation of connections [Roth-96, p. 148] (English translation added)

3.2 Koller

Koller [Koller in Bauer et al.-91, pp. 2-25] defines a connection as the function *f* (*e*, *m*, *g*) with:

e: the *physical effect* restricting movements between the components;
m: the *material* of the components and the additives;
g: the *geometry* of the connection.

Designing connections means to match these parameters.

For this, Koller focuses on the following physical effects: adhesion, cohesion, surface tension, Hooke's law, aero-/ hydrostatic, aero-/ hydrodynamic, negative pressure, gravitation, electrostatic forces, ferro-/ para-/ electric-/ dia-magnetism, friction according to Coulomb/ Eytelwein/ Newton, buoyancy, centrifugal and inert force, impetus [Koller in Bauer et al.-91, pp. 4].

Components and additives can be of any material. For determining the connection geometry, Koller focuses on the variation of interfaces concerning: dimensions, shape, number, position, order, and structure [Koller in Bauer et al.-91, p. 11].

In Figure 3-5 Koller shows the variety of the connection geometry resulting from systematically varying the shape of the component interfaces.

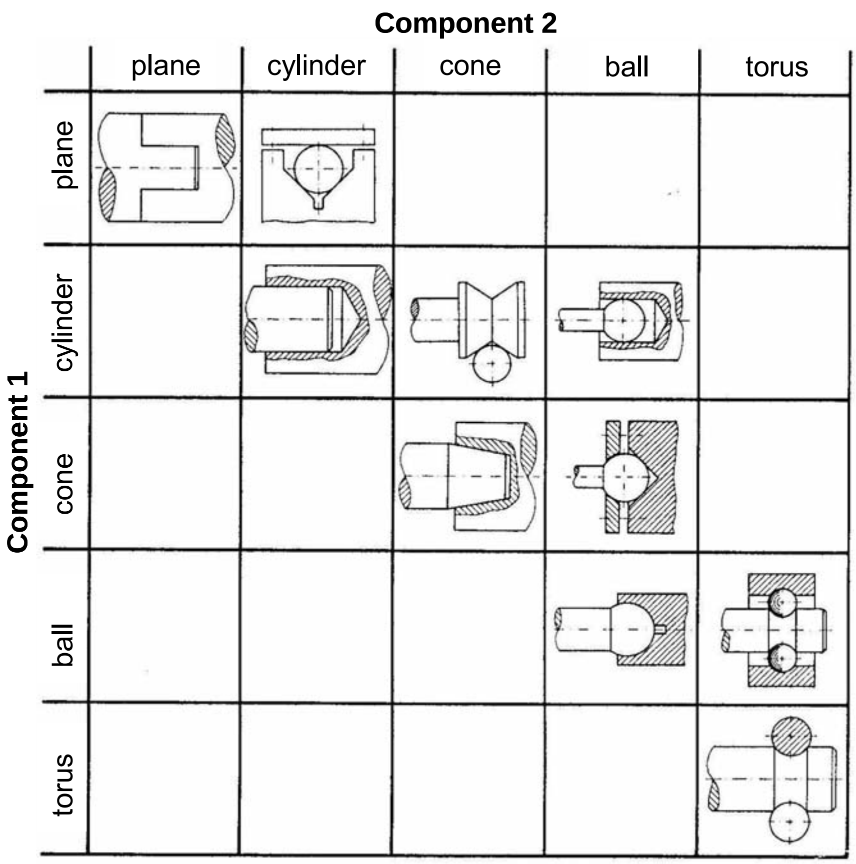
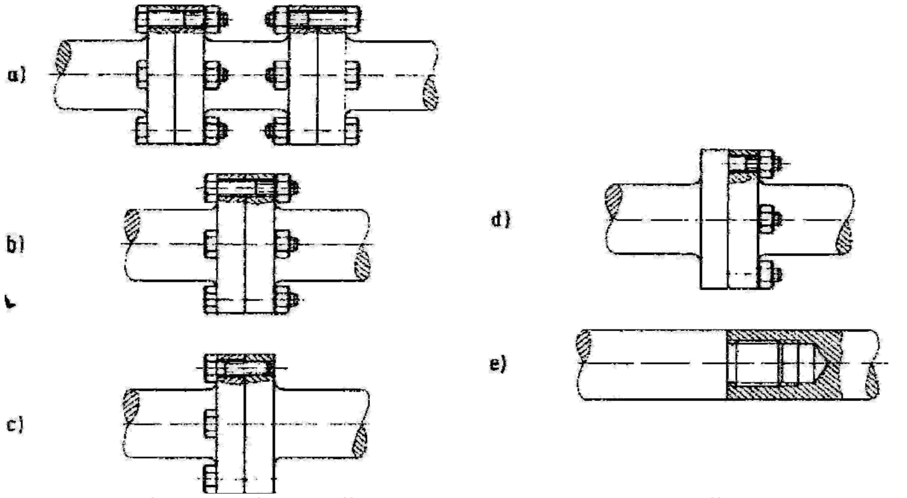


Figure 3-5: Systematic variation of the component interfaces [Koller in Bauer-91, p. 12] (English translation added)

As another possibility for achieving connections with different geometries, Koller suggests to vary the level of fastener integration into the components. This can be realised through applying different construction methods (Figure 3-6).



a) Indirect connection of two shafts in differential construction method (Differentialbauweise) with additional components (Hilfsbauteile);
b) direct connection in differential construction method;
c) direct connection in partially-integrated construction method (teilintegrierte Bauweise);
d) direct connection in partially-integrated construction method;
e) direct connection in fully-integrated construction method (vollintegrierte Bauweise).

Figure 3-6: Variation of the construction method [Koller in Bauer-91, p. 13] (English translation added)

3.3 Ehrlenspiel

Ehrlenspiel aims to realise a computer-aided process for the design of connections supporting the selection of available connections as well as their dimensioning. From VDI 2221 [VDI 2221-93] he derives a *connection model* dividing connections in *connection faces*, *connection spaces* and *connection structures* [Ehrlenspiel et al.-92, pp. 182], and a *systematic process for designing connections* [Ehrlenspiel et al.-92, p. 190]. This process consists of the following steps:

Step 1: Specification of the connection requirements;

Step 2: Specification of the required degree of freedom;

Step 3: Investigation of physical effects that restrict movement;

Step 4: Selection of suitable connections;

Step 5: Arrangement of the connections;

Step 6: Dimensioning of the connections;

Step 7: Documentation for the realisation and utilisation of the connections.

With the connection model and the connection design process, Ehrlenspiel developed a computer tool with two interacting modules, the *design module* (Gestaltmodul) and the *information module* (Informationsmodul).

The design module is a feature-based CAD-system linked to a database with connections. These connections are represented as features to be dimensioned, i.e. parametric design, and must be positioned by the designer. The features provide further functionalities, e.g. the determination of suitable counter geometries for engaging the hook of a snap fit connection. For adapting the snap fit connection to the components to be assembled, the feature allocates the component material to the hook and the counter geometry. The design module provides the following support:

- identification and completion of requirements (step 1);
- analysis of necessary changes of the connections caused by changes of the components, e.g. indication of fasteners to be modified, if component materials change (step 2);
- detection of missing connection faces through the performance of a force flow analysis (step 2);
- realisation of the connection geometry (step 3 to 6);
- performance of an assembly analysis (step 5 to 7);
- interaction with the information module, e.g. to check availability of tools for the automatic assembly of screws (step 7).

The information module contains the following:

- checklists for requirements for the entire product life cycle including (dis)assembly (step 1);
- design catalogues of connections (step 1, 3 to 5);
- information about available production and manufacturing facilities (step 4 to 6);
- information about applicable materials (step 4, 6);
- calculation methods (step 6);
- information about operation and service properties of specific connections (step 4, 7);
- reference to FEM-calculations and tests (step 7).

3.4 LeBacq et al.

LeBacq et al. [LeBacq et al.-02] developed a software tool for supporting the selection of adhesive-, welding- and mechanical connections. For this, electronic datasheets are prepared specifying each considered connection concerning its:

- function;
- assembly process;
- suitability concerning materials;
- geometry.

The datasheets are stored in a database. If a connection is to be designed, the requirements are recorded through an electronic questionnaire based on the specification in the datasheets. By comparing datasheets and questionnaire, connections are ranked according to their suitability.

3.5 Suhr

The approach of Suhr [Suhr–96] is similar to the approach of Lebacq. Connections are classified using 15 criteria and the resulting information is stored in a database. For selecting suitable connections, requirements referring to the criteria must be specified. Through comparison of the requirements and the information in the database, the best matching connections are proposed.

3.6 Discussion

Roth’s locking and kind of locking matrices (Section 3.1.1) are not directly supporting the design of connections. However, they are useful for indicating the movements to be restricted in a connection and for checking the applicability of selected or generated connections.

Roth’s design catalogues (Section 3.1.2) provide the possibility of selecting available connections as well as generating novel ones. However, the generation of novel connections is not further supported and the interface geometry of the components to be assembled is not considered. Concerning the selection process, the consideration of different concretisation levels and the reference to further design catalogues provides some guidance. Decision making is supported through the classification-, main- and access sections, and an appendix. If design catalogues are not available for the considered task or if new solution variants are to be added, considerably effort is required for the preparation or updating of design catalogues.

Roth’s morphological chart for the generation of novel connections (Section 3.1.3) is more a concept than a concrete approach. Without having predefined some connection characteristics, there leave too many characteristics to be determined and at the same time many restrictions exist concerning their suitable combination. Thus, the generation of novel connections is hardly supported through the morphological chart. The chart could be useful for the systematic improvement of available connections through focusing only on some characteristics and their values.

With the function f(e, m, g), Koller presents the solution space of connections in an abstracted way and thus considers available as well as novel connections. He also considers the interface geometry of the components to be assembled. However, a design process or support for decision making is not provided.

For realising the approach of Ehrlenspiel (Section 3.3), much information must be collected and high effort for developing the software is necessary. The number of considered connections is restricted and the generation of novel ones is not supported. Also the interface geometry of the components to be assembled is not considered. However, the designer is guided through the design process, and decision making is supported.

Similarly, the approaches of LeBacq et al. (Section 3.4) and Suhr (Section 3.5) consider only a restricted number of connections and are not supporting the generation of novel ones while a guide through the design process and support of decision making are provided. Suhr also considers the interface geometries of the components to be assembled by dividing these in plane and bent. However, this is too general for really supporting the process of designing connections.

The investigated approaches have not turned out satisfactory because they are neither considering generation methods for novel connections nor do they consider the interface geometry of the components to be assembled. Further, most of the approaches require a high preparation and maintenance effort.

Connections play a decisive role for the design of successful products (Section 1.1), designing satisfying connections is a complex process (Section 2.1) and existing approaches require high preparation and maintenance efforts, are not supporting the selection of existing and the generation of novel connections, and usually the interface geometries of the components to be assembled are not considered. For this reason a new approach, SYCONDE, has been developed (Chapter 5).

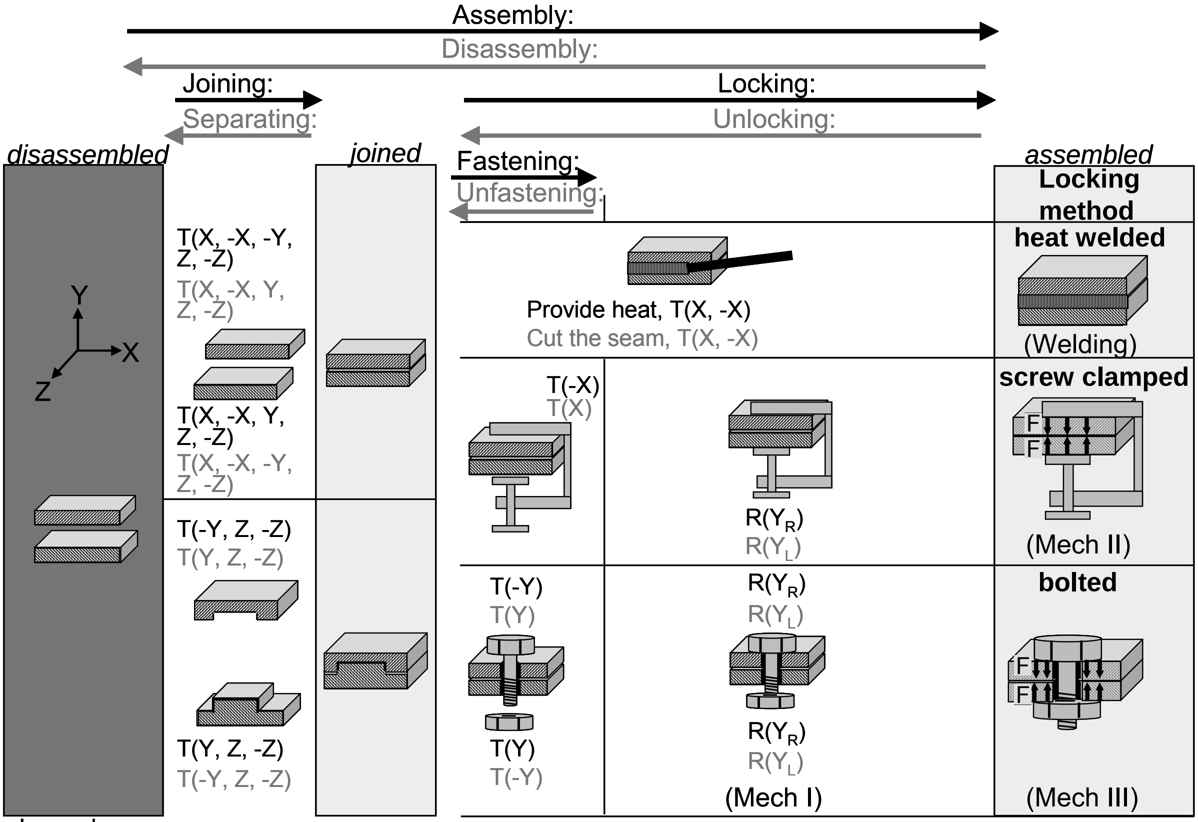
4 Connections: Properties, characteristics, classification

In this chapter (dis)assembly related properties and connection characteristics are linked to each other (Section 4.1). New connection principles are introduced that focus on both working principles and geometrical characteristics (Section 4.2). Referring to the first research question of how the solution space of connections can be holistically represented, a new classification scheme of connections is proposed (Section 4.3).

4.1 (Dis)assembly related properties and connection characteristics

In order to clearly and accurately link (dis)assembly related properties and connection characteristics to each other, (dis)assembly is split in subprocesses. The assembly subprocesses are *joining*, i.e. combining two or more single components such that the locking process can be performed, and *locking*, i.e. maintaining the joined state of the components under loading. In analogy, the disassembly subprocesses are *unlocking*, i.e. enabling separation of the components, and *separating*, i.e. moving the components apart from each other. *Material* can additionally be necessary for materially locked connections, e.g. solder and adhesives, and *fasteners* for those mechanically locked, e.g. screw or clamp. Unlike material, which changes its state of aggregation during (dis)assembly, fasteners retain their state of aggregation. Thus, processes for providing and removing particular fasteners can exactly be specified. To separately consider these processes, these are defined within the locking and unlocking processes as *fastening* and *unfastening*.

Figure 4-1 displays the specific (dis)assembly subprocesses by means of different connections, namely a heat-welded connection (first row), a screw-clamped connection (second row) and a bolted connection (third row). The assembly subprocesses are obtained through reading the scheme from left to right; the disassembly subprocesses through reading from right to left. The first, the third and the last column classify the assembly states, namely *disassembled*, *joined* and *assembled*. The subprocesses, i.e. joining/separating (second column) and locking/unlocking (fourth and fifth column) with fastening/unfastening (fourth column) are described through sketches, activities and translatory (T) as well as rotatory (R) movements. Directions are indicated according to the orthogonal system in the first column. The second column shows for the considered connections that different interface geometries result in different joining and separating movements. Also the locking processes are different for each connection. For the heat-welded connection only one locking process is necessary, namely the provision of heat along the component interfaces. For the screw-clamped connection and the bolted connection the locking process also contains separate fastening processes.



Legend:

T:	translatory movement;
R:	rotatory movement;
(X, Y, Z, -X, -Y, -Z):	direction of translatory movement (T) / axis of rotatory movement (R) ;
(X_R, Y_R, Z_R):	movement in clockwise direction;
(X_L, Y_L, Z_L):	movement in counterclockwise direction;
F:	locking force.

Figure 4-1: (Dis)assembly subprocesses of different connections

Due to the fact, that locking is a prerequisite of every connection and joining always must be realised such that locking is possible, locking and unlocking properties and the corresponding connection characteristics are considered first (Section 4.1.1). Later on (Section 4.1.2) the focus is on joining and separating properties and the corresponding connection characteristics.

4.1.1 Locking and unlocking properties and connection characteristics

The locking and unlocking properties of connections depend on their working principles and physical effects. Koller most extensively classified physical effects for connections (Section 3.2). Of the physical effects mentioned by Koller, *surface tension*, *gravitation* and *buoyancy* are not realising a fixed arrangement in all orientations while *aero-/hydrostatics*, *aero-/hydrodynamics*, *electrostatic forces*, *electric magnetism*, *centrifugal and inert force* as well as *impetus* cannot hold a fixed arrangement without the supply of energy. Thus, these physical effects cannot be used for connections considered in this thesis (Section 1.3) and are for this reason not further considered here. *Hooke's law* and *friction* are combined to *friction* because if high enough, both physical effects are causing the same locking, namely static friction. Working principles and physical effects are hereinafter summarised as working principles.

The working principles further considered for connections are thus:

- adhesion;
- cohesion;
- negative pressure;
- magnetism through permanent magnets;
- friction.

The working principle adhesion is further split in:

- *chemical adhesion*, e.g. soldering;
- *microstructural mechanical adhesion*, e.g. gluing;
- *macrostructural mechanical adhesion*, e.g. snap fit.

The main activity of the designer determining the locking and unlocking properties of connections is to select and generate *effect carriers* restricting movements between components. For this reason working principles are clustered in accordance with their effect carriers in the following kinds of locking [Klett & Blessing-06]:

- *force field locking*, with *non-material* effect carriers;
- *material locking*, with the effect carrier *material*;
- *mechanical locking*, with the effect carrier *geometry*.

Friction is involved in force field- or mechanical locking and for this reason is allocated to both kinds of locking.

In line with Figure 4-1, mechanical locking is split into three locking technologies:

- *Mech I* is realised through macrostructural mechanical adhesion. In unloaded state, no force is effective and clearance between the components remains, e.g. loose bolted connection, snap fit connection;
- *Mech II* is realised through mechanically transmitted forces resulting in static friction, e. g. preloaded screw-clamp connection;
- *Mech III* is realised through both macrostructural mechanical adhesion and mechanically transmitted forces resulting in static friction, e.g. preloaded bolt-nut connection.

As a summary, Table 4-1 allocates to each kind of locking, the working principles for restricting movements, the effect carriers, the locking technologies, the locking and unlocking processes, as well as an application field. The described unlocking processes are the reversed locking processes. If a locking process cannot be reversed, the commonly used unlocking process is given and marked by * in Table 4-1.

Table 4-1a: Kinds of locking, continuation on next page

Kind of locking	**Working principle**	**Effect carrier**	**Locking technology**	**Locking process**	**Unlocking process**	**Application example**
Force field locking	Magnetism through permanent magnets + Static friction	Non-material	Permanent magnet technology	Moving the components together.	Moving the components apart from each other.	Combining permanent magnet and ferro-magnetic component
	Negative pressure + Static friction		Vacuum technology	Combining the components under vacuum and carry these to ambient.	Carrying the components into a vacuum environment.	Applying a suction cup
				Decreasing the pressure within the interface.	Providing ambient pressure within the interface.	
Material locking	Cohesion (if materials are identical) or Chemical adhesion (if materials are different)	Material	Welding technology	Liquefying the component interfaces through heat and merging these.	Liquefying the component interfaces through heat and moving these apart.	Laser arc welding
				Liquefying the interfaces through friction and merging these.		Friction welding
				Merging the interfaces through high-speed deformation.	*Deforming the components.	Explosion welding
	Chemical adhesion		Soldering/ brazing technology	Providing liquefied solder/braze to the interfaces of the positioned components.	Liquefying the solder/braze through heat and moving the components apart.	Resistance soldering
			Adhesive technology	Providing adhesive to the component interfaces and perform hardening process.	*Solubilising adhesive through acids, UV-light or heat.	Adhering with reaction adhesive

*: commonly used unlocking process (locking process cannot be reversed).

Table 4-1b: Kinds of locking, continuation

Kind of locking	**Working principle**	**Effect carrier**	**Locking technology**	**Locking process**	**Unlocking process**	**Applica-tion example**
Material locking	Micro-structural mechanical adhesion	Material	Gluing technology	Providing glue to the component interfaces and perform solidification process.	*Solubilising glue through acids, UV-light or heat to the interface.	Gluing with cement
Mech-anical locking	Macro-structural mechanical adhesion	Geo-metry	Mech I	Combining the component interfaces through movements and/or forces.	Separating the component interfaces through movements and/or forces.	Loosely applying a bolt-nut connection or a snap fit connection
	Mechanically transmitted force + Static friction		Mech II	Clamping the components through movement and/or forces.	Undoing clamping of the components through movements and/or forces.	Tightly applying a screw-clamp
	Macro-structural mechanical adhesion + Mechanically transmitted force + Static friction		Mech III	Combining the component interfaces and clamping the components through movements and/or forces.	Undoing clamping of the components and separating the component interfaces through movements and/or forces.	Tightly applying a bolt-nut connection

*: commonly used unlocking process (locking process cannot be reversed).

4.1.2 Joining and separating properties and connection characteristics

In accordance with the orientation of their normal vectors, component interfaces are geometrically classified in *planar* and *profiled*. Planar interfaces have parallel normal vectors; profiled interfaces have diverging or intersecting normal vectors. The profiled ones are further classified in *convex*, i.e. interfaces with diverging normal vectors, and *concave*, i.e. interfaces with intersecting normal vectors. This results in the interface types illustrated in Figure 4-2.

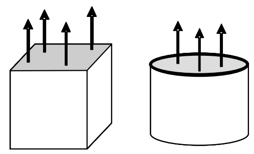
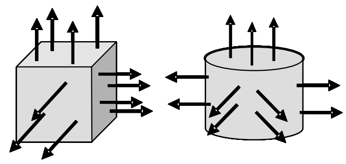
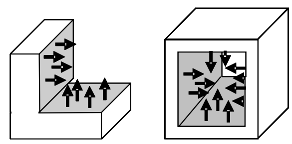
Interface type	**Planar,** i.e. parallel normal vectors	**Convex,** i.e. diverging normal vectors	**Concave,** i.e. intersecting normal vectors
Sketch Faces representing the interface are grey.	 Cuboid: single face Cylinder: single basic face	 Cuboid: from two up to all faces. Cylinder: -lateral face; -more than two faces.	 Faces of a notch Faces of a hole

Figure 4-2: Interface types

If these interface types are combined with each other, two useful combinations namely planar/planar and convex/concave emerge. Components joined through planar interfaces are defined as a *planar joining concept*, abbreviated by *p*; those joined through convex and concave interfaces are defined as *convex/concave joining concept*, abbreviated by *cc*. Planar joining concepts only restrict one relative movement while convex/concave ones restrict between two and five. This results in different degrees of freedoms and implies that components of planar joining concepts can be joined and separated in five directions while those of convex/concave joining concepts can be joined and separated from one to four directions (Figure 4-3).

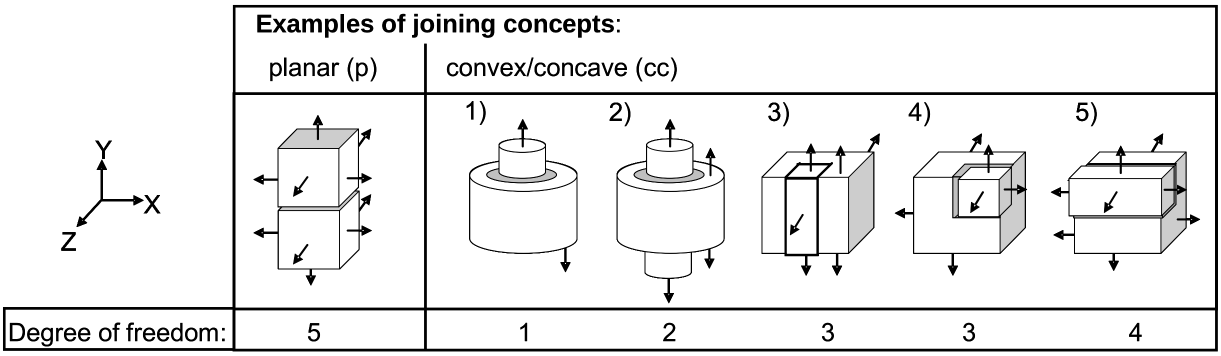


Figure 4-3: Degrees of freedom of different joining concepts

If a concave interface consists of faces aligned relatively to each other under an angle α larger than 270°, the faces are defined as being situated opposite each other. In Figure 4-4 this is illustrated by examples of concave interfaces with opposite and not opposite situated faces.

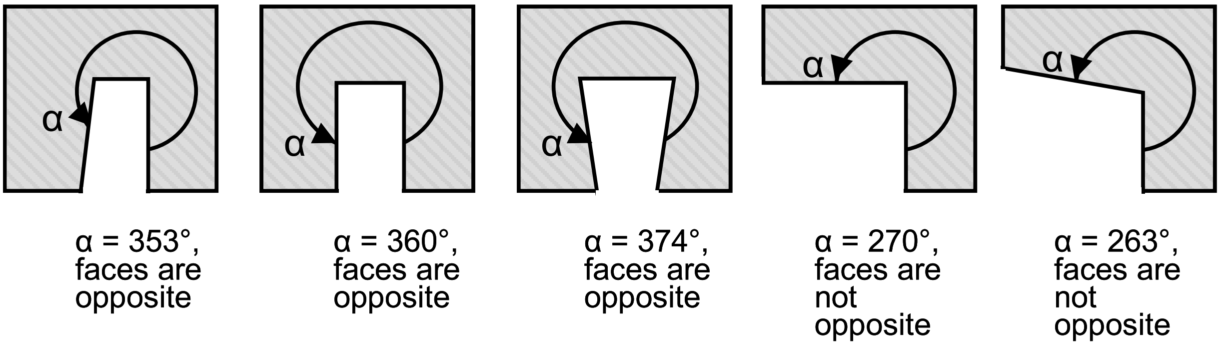


Figure 4-4: Examples of concave interfaces with opposite and not opposite situated faces

A component with concave interface and opposite situated faces can entangle a component with a corresponding convex interface (see convex/concave joining concepts no. 1 – 3 in Figure 4-3). In this case, locking through static friction can be realised through mechanically transmitting a force between the opposite situated interface areas. This is the basis for connections like press fits and those realised through hose clamps or wedges (Figure 4-5).

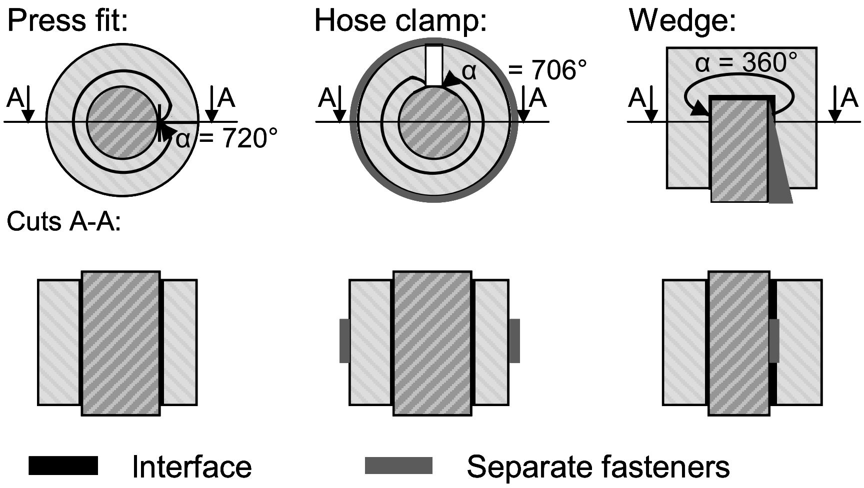


Figure 4-5: Cross sections of connections locked through concave interfaces with opposite situated faces

In accordance with their different interface characteristics and locking properties, convex/concave joining concepts are classified (Figure 4-6) into:

- *type A*-joining concepts without opposite situated interface areas, abbreviated through *ccA* (see convex/concave joining concepts no. 4 and 5 in Figure 4-3);
- *type B*–joining concepts with opposite situated interface areas, abbreviated through *ccB* (see convex/concave joining concepts no. 1 - 3 in Figure 4-3).

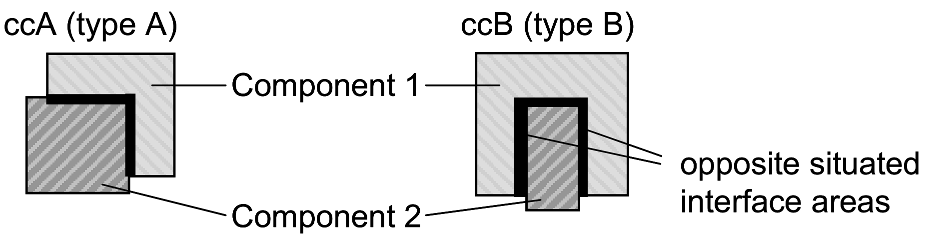


Figure 4-6: Examples of ccA - and ccB - joining concepts

The possible joining and separating movements of the classified joining concepts are summarised in Table 4-2.

Table 4-2: Joining and separating movements of p-, ccA- and ccB-joining concepts

Joining concept	Joining movements	Separating movements
p (planar)	5 directions; 4 directions remain free when components are contacted, e.g. for positioning.	5 directions
ccA (convex/concave type A)	3-4* directions; 0 or 2* directions remain free when components are contacted, e.g. for positioning.	3-4* directions
ccB (convex/concave type B)	1-3* directions; 0 or 2* directions remain free when components are contacted, e.g. for positioning.	1-3* directions
*The exact amount of directions depends on the interface geometry, see also Figure 4-3.		

4.2 Connection principles

Connection principles are introduced as descriptions of connections focusing on their working principles and geometrical characteristics at the same time. A connection principle is created through combining the kind of locking (Section 4.1.1) and the joining concept (Section 4.1.2) and is illustrated as a cross section of the connection without specifying its details, e.g. type of adhesive or fastener. First, the connection principles with force field and material locking are described, then those with mechanical locking.

Force field and material locking are realised at the component interfaces. The cross sections of the possibly resulting connections are identical for both kinds of locking and are represented through the connection principles in Figure 4-7.

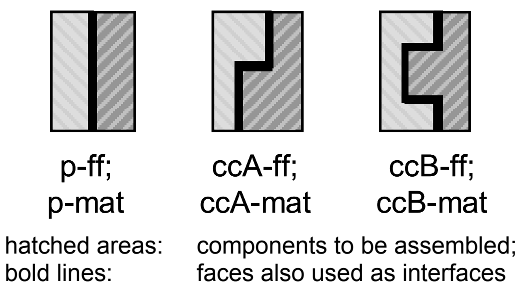
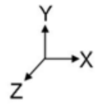


Figure 4-7: Connection principles for force field- (ff-) and material- (mat-) locked joining concepts

Mechanical locking can be realised through the interfaces of the components to be assembled, or through additives, i.e. fasteners. Fasteners initiate locking from outside the component interfaces and can be placed at different locations, e.g. they can entangle or pierce the components. This results in a large number of connection principles. Two types of connection principles, the *standard* and the *special connection principle*, are distinguished. The standard connection principles can be realised with all joining concept types, i.e. p, ccA and ccB (Section 4.1.2); the special ones can only be realised with ccB joining concepts. In Table 4-3 the connection principles with mechanical locking are listed. Each of these is provided with an identifier and a set of cross sections of the different joining concepts. The geometrical structure of the connection principles is explained and examples of locking methods are given. Some of the locking methods shown in Table 4-3 can be applied on more than one connection principle. Table 4-3 should represent the largest space of connections but cannot be exhaustive. Three points in the last row of each list illustrate that further connection principles can be added, if necessary.

Table 4-3a: Connection principles for mechanically locked joining concepts, continuation on next page

Standard connection principles for all joining concepts, i.e. p; ccA, ccB.
hatched areas: components to be assembled;
black bold line: locking initiation though interfaces of components to be assembled;
fully grey: locking initiation through fastener;
arrow (→) possibility of force application.



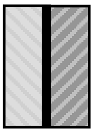
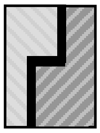
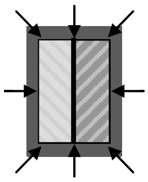
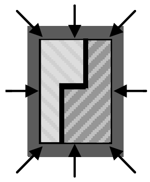
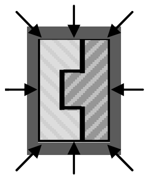
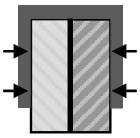
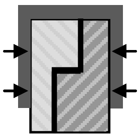
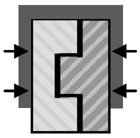
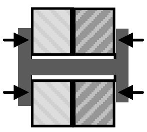
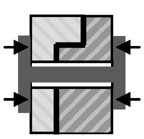
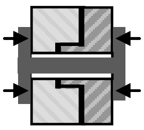
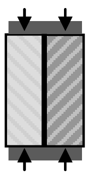
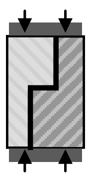
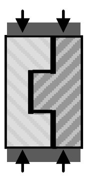
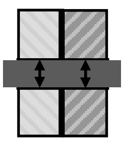
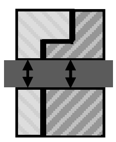
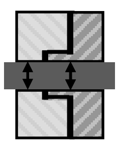
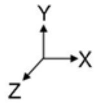
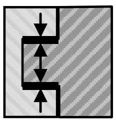
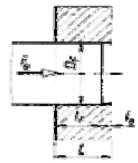
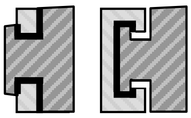
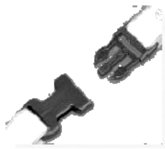
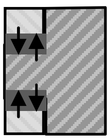
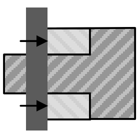
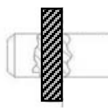
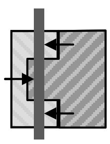
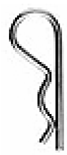
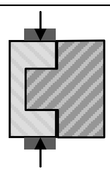
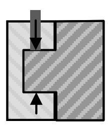
Id.	Cross section p	Cross section ccA	Cross section ccB	Description	Example of locking methods
A1			see connection principle B2	Locking is initiated at the component interfaces through geometrical interaction	 Interfaces with Velcro-structure
A2				Locking is initiated at the component contour through faces perpendicular to the XY-plane. The fastener entangles the components completely.	 Cable tie
A3				Locking is initiated at the component contour through faces parallel to the YZ-plane. The fastener does not entangle the components completely.	 Screw-clamp
A4				Locking is initiated at the component contour through faces parallel to the YZ-plane. The fastener pierces the components.	 Bolt and nut
A5				Locking is initiated at the component contour through faces perpendicular to the YZ-plane. The fastener entangles the components partly or completely.	 Hose clamp
A6				Locking is initiated within the component contour through faces perpendicular to the YZ-plane. The fastener pierces the components.	 Pin
	…				

Table 4-3b: Connection principles for mechanically locked joining concepts, continuation

Special connection principles for ccB joining concepts, only.
hatched areas: components to be assembled;
black bold line: locking initiation though interfaces of components to be assembled;
fully grey: locking initiation through fastener;
arrow (→) possibility of force application.



Id.	Cross section	Description	Example of locking methods
B1		Locking is initiated at the component interfaces perpendicular to the YZ-plane through forces resulting from corresponding interface dimensions.	 Press fit
B2		Locking in X direction is initiated at the component interfaces parallel to the YZ-plane; locking in Y and Z direction is initiated at the component interfaces perpendicular to the YZ-plane. All directions are locked through geometrical interaction.	 Snap fit
B3		Locking is initiated at the component interfaces perpendicular to the YZ-plane. The fastener is placed between the component interfaces.	 Clamping collar
B4		At the concave component, locking is initiated at the contour; at the convex component locking is initiated within the contour. The faces where locking is initiated are parallel to the YZ-plane. The fastener contacts the concave component and pierces the convex component.	 Splint
B5		Locking is initiated within the contour of the components at faces parallel to the YZ-plane. The fastener pierces both components.	 Spring split pin
B6		Locking is initiated at the contour of the concave component and at the interface of the concave and the convex component through faces perpendicular to the YZ-plane. The fastener entangles the components partly or completely.	 Clamping hose clamp
B7		Locking is initiated within the contour of the concave component and at the interface of concave and convex components through faces perpendicular to the YZ-plane. The fastener pierces the concave component.	 Grub screw
	…		

4.3 New connection classification scheme

Based on the definitions in Section 4.1 and the connection principles in Section 4.2, a new connection classification scheme (Figure 4-8) has been developed representing the solution space of the connections considered in this thesis (Section 1.3).

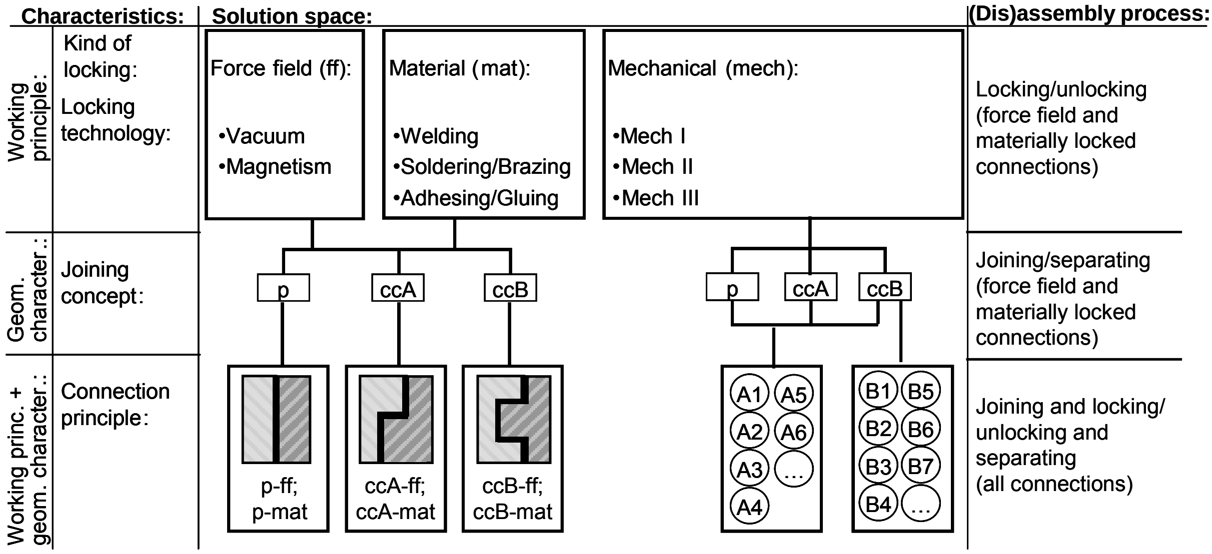


Figure 4-8: New connection classification scheme

The working principle of any connection is described through the kind of locking and the locking technology, both defined in Section 4.1.1. The geometrical characteristics of a force field and materially locked connection as well as the component geometry of a mechanically locked connection are described through the joining concept defined in Section 4.1.2. The geometrical characteristics of a mechanically locked connection, i.e. the interaction between the components and the general geometry of the fasteners, are described through the connection principle defined in Section 4.2. For the description of each characteristic, i.e. kind of locking, locking technology, joining concept and connection principle, the solution space defined in Sections 4.1 - 4.3 is available.

Only for force field or materially locked connections (un)locking processes and joining/separating processes can be determined through the locking technology and the joining concept respectively. For mechanically locked connections (un)locking, joining and separating processes are determined through the connection principle.

The scheme supports the selection and generation of connections and is the basis for SYCONDE, the proposed approach for designing connections, which is discussed in the following chapter.

5 SYCONDE - a new approach for designing connections

A new approach for supporting the process of designing, i.e. selecting and generating, connections under holistic consideration of the solution space was developed. This approach is called SYCONDE, SYstematic COnnection DEsign, and bases on the new connection classification scheme described in Section 4.3. In Section 5.1 the requirements on SYCONDE are summarised. The general description of a systematic connection design process is given in Section 5.2. The realisation and the particular steps of SYCONDE are described in Section 5.3.

5.1 Requirements on SYCONDE

With SYCONDE, an effective and efficient approach for designing connections should be realised. The approach should support the selection of available connections in order to prevent generating these again, and the generation of novel ones. For this, the solution space and the already considered connection variants should be identified such that the not yet considered solution space can be estimated. Further, the approach should consider the geometry of the interface of the components to be assembled. The designer should be guided through the design process and decision making should be supported.

5.2 General description of a systematic connection design process

Before starting with designing a connection, it must be checked, if a connection is really necessary. If this is confirmed, the characteristics of the components to be assembled and the connection requirements are to be defined. In accordance with these, the connection characteristics are to be determined. The connection characteristics and the solution space are covered by Figure 4-8. Unlike the classification of connections where the characteristics only must be selected, the process of designing connections requires their combination. For illustrating the connection design process, Figure 4-8 was completed with the combination steps and resulted in Figure 5-1 illustrating the characteristics, their solution space and their necessary combination to connections.

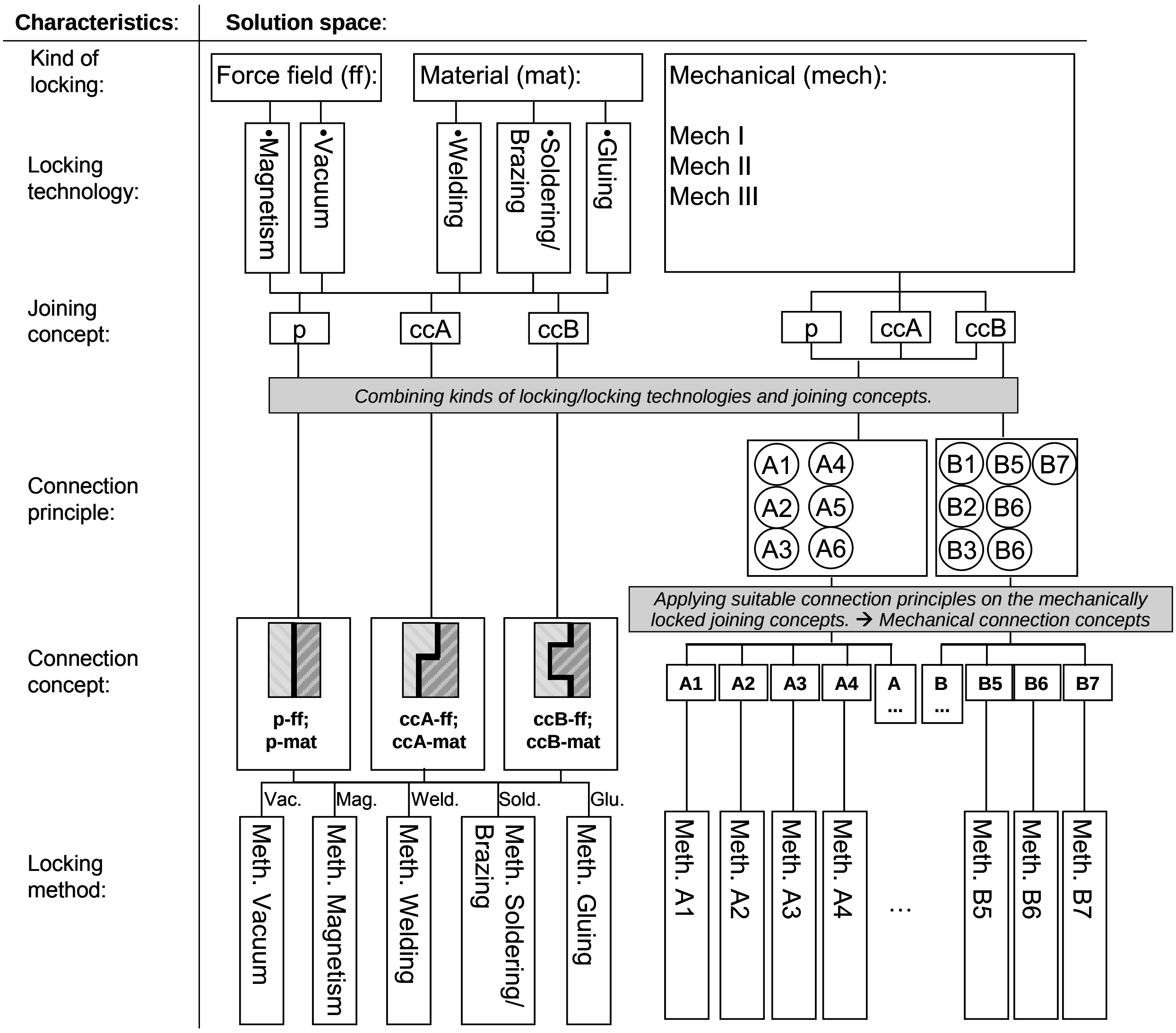


Figure 5-1: Characteristics, their solution space and their combination into connections

As shown in Figure 5-1, suitable kinds of locking or locking technologies as well as joining concepts are to be selected and combined. With force field and material kind of locking, this already results in connection concepts. For realising mechanical connection concepts, connection principles must be selected or generated first and then applied to the mechanically locked joining concepts. In case many connection concepts emerge, they should be carefully reduced. Finally, suitable locking methods should be selected or generated, and applied to the connection concepts. The resulting connections are to be evaluated and ranked concerning their fulfilment of the requirements.

5.3 Realisation of SYCONDE and its process steps

SYCONDE focuses on those connections considered in this thesis (Section 1.3). On the basis of the systematic connection design process in Section 5.2, the process steps are structured in a flowchart together with the intended results (Figure 5-2).

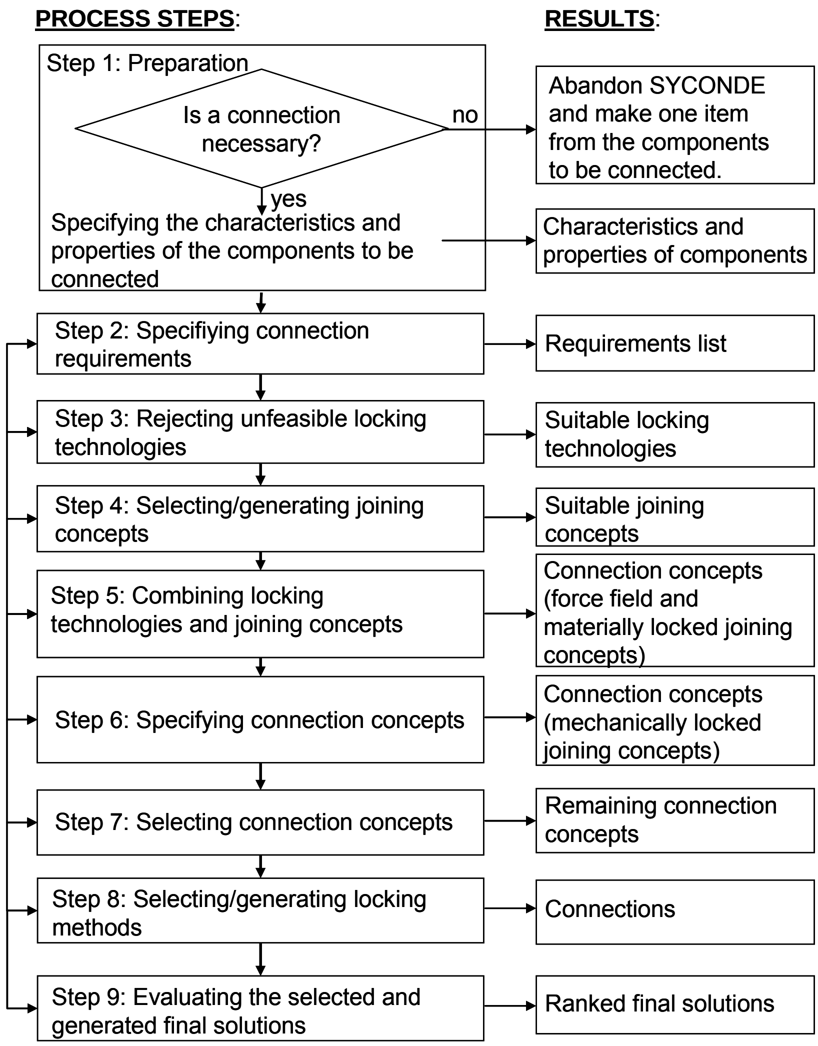


Figure 5-2: Flowchart for SYCONDE

SYCONDE provides a *workbook*, a set of *documentation forms* and some leaflets with *supportive information*. These can be found in Appendix C. In the workbook, each step is described by the actions to be taken and a suggestion for the satisfaction of each relevant requirement is given. The documentation forms contain the question scheme, the component scheme, the requirements list, the combination scheme, the connection principles scheme, the selection chart, the final solution form, and the evaluation chart. These facilitate recording the resulting connections also called *final solutions* as well as the intermediate results also called *solution variants*, i.e. the selected or generated kinds of locking, locking technologies, joining concepts, connection principles, connection concepts and locking methods. The supportive information consists of the locking technology list and the locking methods lists. These ease the selection, rejection and generation of solution variants. In Figure 5-3 the documentation forms and the supportive information are allocated to the process steps described in the workbook of SYCONDE. The steps are explained below. An example of a design process with SYCONDE is given in Appendix C.1.

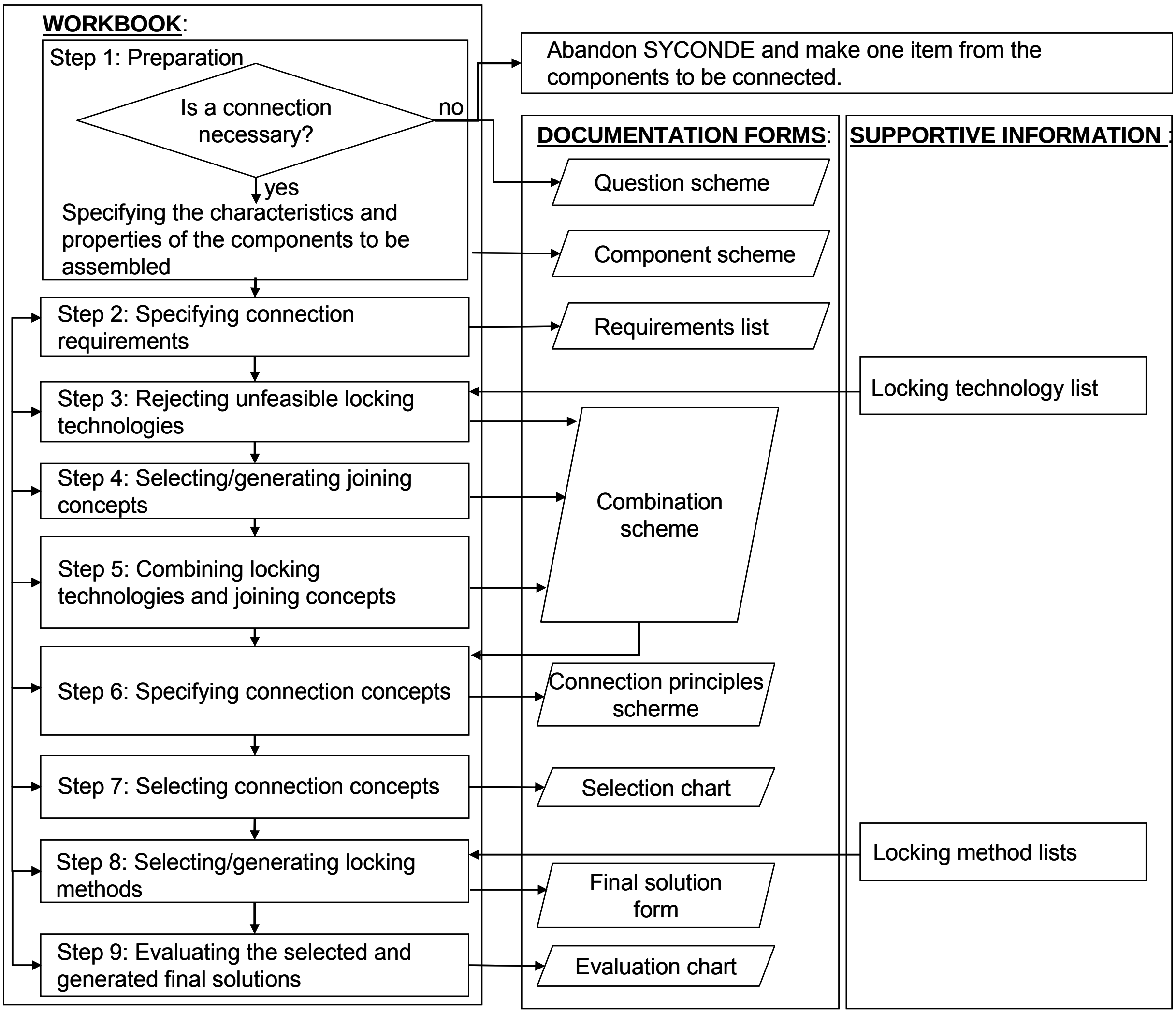


Figure 5-3: Allocation of SYCONDE steps, documentation forms and supportive information

5.3.1 Step 1: Preparation

Due to the fact that the design and maintenance of connections cause efforts, and connections often cause failure, there must be sound reasons for a connection instead of combining the components to be assembled into one component. Boothroyd and Dewhurst [Boothroyd & Dewhurst–87] defined the following questions to be answered positively for confirming the necessity of a connection:

- Do the components move relatively to each other during product use? Only gross motion should be considered – small motions that can be accommodated by elastic hinges, for example, are not sufficient for a positive answer.
- Must the components be of different materials than or be isolated from each other? Only fundamental reasons concerned with material properties are acceptable.
- Must the components be separated from each other because otherwise necessary assembly or disassembly of other separate components would be impossible?

The following questions were added:

- Are there other reasons for separating the components, e.g. components are produced cheaper in different locations?
- Is at least one of the components used in different assemblies and for this reason must be separately available?

For detecting the necessity of a connection, the designer is asked to answer these questions in a *question scheme* (Appendix C.1, Figure C-1) by ticking boxes. If all answers are negative, it is recommended to combine the components into one component and to abandon SYCONDE. If at least one of the answers is positive, a connection is necessary and SYCONDE is continued. In this case, the components to be assembled are clearly identified as component 1, component 2, …, component n, their materials are specified and the resulting information is documented in the *component scheme* (Appendix C.1, Figure C-2).

5.3.2 Step 2: Specifying connection requirements

The set of documentation forms consists of a requirements list with SYCONDE requirements (Figure 5-4). In this list, designers are asked to state the importance of the given requirements through ticking D or W (D = demand; W = wish). Demands (D) must be satisfied. The satisfaction of wishes (W) is not obligatory but would be advantageous. The designer can add further requirements. In accordance with their relevance, the requirements are allocated to the steps of SYCONDE. This is marked in the column ‘Used in step’ in Figure 5-4. Once the process is computer-aided, for each step only the relevant requirements labelled with D or W will be shown.

In Appendix C.1, Figure C-3, a filled in requirements list can be found. This requirements list is the old version and thus slightly differs from the one shown in Figure 5-4.

No.	Used in step	Connection requirements	D	W
1	**Requirements concerning the components**			
1.1	3; 8(ff & mat)	The material of component 1 should not be changed.		
1.2	3; 8(ff & mat)	The material of component 2 should not be changed.		
1.3	4; 6; 8mech	A shape change of component 1 is not possible or only under restrictions.		
1.4	4; 6; 8mech	A shape change of component 2 is not possible or only under restrictions.		
…	…	…		
2	**Requirements concerning the connection function**			
2.1	3; 6; 8(ff & mech)	Further components are to be attached through the connection.		
2.2	8mech	To prevent movements or vibrations, the connection should be free of clearance.		
2.3	3	The connection should withstand dynamical stress.		
2.4	8mat	The connection should work between the following temperatures:________		
2.5	4; 5; 8mech;	The unintended unlocking and separating of the components has highly negative effects, e.g. danger for live or health. Hence, higher safety standards against unlocking and separating of the components should be achieved.		
…	…	…		
3	**Requirements concerning the assembly and disassembly processes**			
3.1	3; 8mat	Locking should be achieved through movement and/or deformation.		
3.2	8mat	Unlocking should be achieved through movement and/or deformation.		
3.3	3; 4; 6; 8(mat & mech)	Additives, i.e. materials or fasteners, should not be used.		
3.4	3; 8(mat & mech)	Geometry or molecular structure of the components should not change through locking and unlocking. This is a prerequisite for a connection that frequently can be assembled and disassembled.		
3.5	3; 8mech	Additives, i.e. materials or fasteners, should withstand frequent locking and unlocking cycles.		
3.6	4;	Joining and/or separating should be possible in many directions.		
3.7	4;	Joining and/or separating should be realised on little space.		
3.8	8(ff & mech)	Assembly subprocesses should be performed through identical triggers.		
3.9	8(ff & mech)	Disassembly subprocesses should be performed through identical triggers.		
3.10	8(ff & mech)	Locking should be performed manually without a tool.		
3.11	8(ff, mat & mech)	Unlocking should be performed manually without a tool.		
3.12	8(ff, mat & mech)	Locking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously locking “at the push of a button”.		
3.13	8(ff, mat & mech)	Unlocking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously unlocking “at the push of a button”.		
…	…	…		

Figure 5-4: Requirements list template for SYCONDE

5.3.3 Step 3: Rejecting unfeasible locking technologies

From the kinds of locking or locking technologies defined in Section 4.1.1 the unfeasible ones are removed. As mentioned before, the workbook provides for each step suggestions for the satisfaction of the relevant requirements. For satisfying requirement no. 3.3, i.e.

additives should not be used, the suggestion is to favour all locking technologies which require no additives for locking. As supportive information the *locking technology list* (Appendix C.2.1) is provided, describing for each kind of locking or locking technology the feasibility of satisfying each of the relevant requirements and the circumstance under which these can be satisfied. Thus, unfeasible kinds of locking or locking technologies can be identified and are crossed out from the *combination scheme* (Appendix C.1, Figure C-9) so that only feasible ones remain. The combination scheme is one of the documentation forms of SYCONDE.

5.3.4 Step 4: Selecting/generating joining concepts

Suitable interface types are determined for the components to be connected and corresponding joining concepts are selected or generated. The workbook contains a description of characteristics and properties of the interface types and joining concepts classified in Section 4.1.2. As mentioned before, the workbook provides for each step suggestions for the satisfaction of the relevant requirements. For satisfying requirement no. 3.6, i.e. joining and/or separating should be possible in many directions, the suggestion is to favour planar joining concepts. The resulting joining concepts are applied to the components to be connected and documented in the *combination scheme* (Appendix C.1, Figure C-9) as sketches and classified as planar (p), convex/concave type A (ccA) and type B (ccB) joining concepts. The combination scheme is one of the documentation forms of SYCONDE.

5.3.5 Step 5: Combining locking technologies and joining concepts

The feasible kinds of locking or locking technologies of step 3 and the joining concepts of step 4 are combined. As mentioned before, the workbook provides for each step suggestions for the satisfaction of the relevant requirements. For satisfying requirement no. 2.5, i.e. to satisfy higher safety standards, the suggestion is to prefer the combination with convex/concave joining concepts because these absorb loads in more directions than planar ones. The resulting combinations of locking technologies and joining concepts are determined and documented through ticking the corresponding boxes in the *combination scheme* (Appendix C.1, Figure C-9). The combination scheme is one of the documentation forms of SYCONDE. For force field and materially locked joining concepts this already results in connection concepts. For mechanically locked joining concepts, connection concepts are determined in step 6.

5.3.6 Step 6: Specifying connection concepts

In this step, suitable connection concepts for the mechanically locked joining concepts are determined. Connection concepts result from allocating connection principles to joining concepts. The fact that mechanical locking can be initiated directly through the interfaces or outside of these through the remaining component faces results in a large number of connection principles (Section 4.2). Derived from Table 4-3, SYCONDE provides a documentation form called *connection principle scheme* which contains connection principles in the form of sketches and further information about the structure of the connection principles (Appendix C.1, Figure C-10). Novel connection principles can be generated and entered in this scheme. For each mechanically locked joining concept suitable connection principles are selected through ticking the corresponding boxes in the connection principles scheme. As mentioned before, the workbook provides for each step suggestions for the satisfaction of the relevant requirements. For satisfying requirement no. 3.3, i.e. additives should not be used; the suggestion is to select connection principles without separate fasteners or to integrate/attach these into/to the components.

5.3.7 Step 7: Selecting connection concepts

The number of connection concepts can be reduced systematically with the *selection chart* (Appendix C.1, Figure C-11). This documentation form contains criteria for elimination, e.g. the fulfilment of the requirements labelled with D in step 2, and for preference. These criteria can be removed, changed or replaced with others. Each connection concept is entered in the chart and the level of criteria fulfilment as well as the final decision is documented. A connection concept can be accepted (+) or rejected (-). If a decision is actually not possible because of a lack of information concerning the connection concept (?) or the possibility of a change of the requirements (!), the connection concept can be kept provisionally and the decision is postponed until the necessary information is obtained. Only the finally accepted connection concepts are further considered.

5.3.8 Step 8: Selecting/generating locking methods

For the accepted connection concepts suitable locking methods are determined. For each kind of locking different requirements are relevant and thus step 8 is separately described for each kind of locking. As mentioned before, the workbook provides for each step suggestions for the satisfaction of the relevant requirements. In Table 5-1 one of the provided suggestions is listed for each kind of locking.

Table 5-1: Examples from the workbook of suggestions for each kind of locking

Kind of locking:	Force field locking	Material locking	Mechanical locking
Requirement:	No. 3.11: Unlocking should be performed manually without a tool.	No. 2.4: The connection should work between specific temperatures.	No. 3.3: Additives, i.e. materials or fasteners, should not be used.
Suggestion for satisfying the requirement:	To dimension the locking force such, that unlocking can be applied manually, or to integrate/attach elements multiplying the force, e.g. release lever.	To ensure that the connection withstands the demanded/wished temperatures.	To select connection principles without separate fasteners, or to integrate/attach these into/to the components.

For supporting the determination of locking methods, *locking method lists* are provided. Beside the description of existing methods which can be selected, these lists also contain information for supporting the generation of novel ones. For force field and material kind of locking separate lists are available for each locking technology, i.e. vacuum-, welding-, soldering technology, etc. For the mechanical kind of locking a list for each connection principle defined in Section 4.2, i.e. A1–B7, is provided, covering all mechanical locking technologies, i.e. Mech I – Mech III. The locking method lists can be found in Appendix C.2.2.

Final solutions result from applying suitable locking methods to the corresponding connection concepts. Each final solution is to be documented on a separate sheet, the *final solution form* (Appendix C.1, Figures C-13 – C-15). The final solution form is one of the documentation forms of SYCONDE.

5.3.9 Step 9: Evaluating the selected and generated final solutions

The final solutions are evaluated and ranked using the evaluation chart (Appendix C.1, Figure C-16), one of the documentation forms of SYCONDE. The evaluation criteria are based on the requirements labelled with W in step 2. However, further criteria as well as weighting factors can be added. If despite this a clear ranking should not be possible, further evaluation methods are suggested.

6 Evaluation of SYCONDE

This chapter addresses the second research question of whether SYCONDE supports designers in the process of designing connections. It focuses on the evaluation questions (Section 6.1), the set up (Section 6.2), the analysis (Section 6.3) as well as the results (Section 6.4), and the opinions of the designers (Section 6.5). In Section 6.6 conclusions are drawn.

6.1 Evaluation questions

The functions of SYCONDE are:

I to clearly structure the solution path while designing connections;

II to help consider a large solution space while designing connections.

The aims of SYCONDE are:

A to support designers in their design process;

B to increase the effectiveness of the process of designing connections;

C to increase the efficiency of the process of designing connections.

From these functions and aims the following evaluation questions were derived:

I Does SYCONDE clearly structure the solution path while designing connections?

II Does SYCONDE support designers in considering a large solution space while designing connections?

A Does SYCONDE support designers in their design processes?

B Does SYCONDE increase the effectiveness of the process of designing connections?

C Does SYCONDE increase the efficiency of the process of designing connections?

6.2 Set up

For answering the evaluation questions, data was collected of design processes in which two groups of designers worked on the same task. The task was to design as many suitable connections, i.e. final solutions, as possible for assembling the soap container of a washing machine and the frontal counter weight. The task can be found in detail in Appendix D.1.

One group of designers used SYCONDE, the *experimental group* “*EG*“, consisting of five *experimental designers* “*ED*s”. The other group, the *control group* “*CG*“, with five *control designers* “*CD*s” did not use SYCONDE. All designers were engineering design students and

PhD-students who had passed the basic course in mechanical engineering. They had basic knowledge of design methodology and were neither expert in the design of connections nor in the design of washing machines. To ensure that both groups had similar expertise, the designers were allocated to the groups based on their connection design skills and their general design process skills. Further, the English language skills of the designers were determined, because SYCONDE is in English and thus designers working with SYCONDE needed to be familiar with the English language. The skills were determined through a questionnaire with 14 questions to be answered by ticking the most appropriate of five given ratings, i.e. not applicable at all, rather not applicable, neutral, rather applicable, fully applicable.

In separate sittings, the design task was given to each designer and each design process was recorded by two video cameras. One camera was focused on the designer; the other on the documentation. At the beginning of the sitting, each designer obtained the following oral instructions:

- to read carefully the introduction of SYCONDE (only EDs);
- to read carefully the design task;
- to ask, if there are uncertainties concerning the design task;
- to ask, if there are uncertainties concerning SYCONDE (only EDs);
- not to ask about solutions;
- to document the solution path, CDs according to what they find important, EDs through using the SYCONDE documentation forms;
- to sketch their final solutions;
- to think aloud;
- to request breaks when desired;
- to define the end of the design process when satisfactory with the results.

For assuring a neutral documentation of the final solutions, EDs and CDs documented these on identical forms, the final solution forms of SYCONDE (Appendix C.1, Figures C-13 – C-15). Design time was calculated from the time taken at the beginning and at the end of the design process, breaks were subtracted. After having finished working on the design task, all designers filled in a questionnaire concerning their perceptions about the structure of their solution path, the size of the considered solution space, the quality of their final solutions and their efficiency. Further, about statements concerning the most positive and negative experiences during working on the design process was asked. The questionnaire of the EDs additionally focused on the support and the (dis)advantages perceived through SYCONDE.

6.3 Analysis

For deciding about the significance of findings the U test [Pospeschill-06, pp. 424; Sanders-95] was applied. The U test is one of the best-known non-parametric tests for assessing whether two independent samples of observations, sample 1 and sample 2, come from the same distribution. The null hypothesis in the U test is that the two samples are drawn from a single population, and therefore that their probability distributions are equal. It requires the two samples to be independent, and the observations to be ordinal or continuous measurements, i.e. one can at least say, of any two observations, which is the greater. For testing the significance of a difference in observation between both samples, i.e. observation in sample 1 > observation in sample 2, or observation in sample 2 > observation in sample 1, the test is performed as one tail test. For testing whether an observation is equal for both samples, i.e. observation in sample 1 = observation in sample 2, the test is performed as two tail test. For the evaluation of SYCONDE the U test was performed as one tail test as described in the following:

- First, all the observations were arranged into a single ranked series, i.e. all the observations without regard to which sample they are were ranked. Then the ranks for the observations which came from sample 1 and sample 2 were added up.
- Second, the statistic U was calculated for the samples for which the observations were greater by means of the following formulas:

  $U_1 = n_1 \text{ x } n_2 + n_1 (n_1 +1)/2 - R_1$

  $U_2 = n_1 \text{ x } n_2 + n_2 (n_2 +1)/2 - R_2$

  n = sample size of the corresponding sample;
  R = sum of the ranks in the corresponding sample.
- Third, the critical value for U was selected from a table [Sanders-95, pp. 581, A-18]. This was done in correspondence with the sample sizes n_1 and n_2 and the significance level, i.e. α-level. For this evaluation, an α-level of 0.05 was considered acceptable.
- Fourth, the null hypothesis was rejected for those cases where U_1 or $U_2 < U$ was valid. For these cases the α-level was indicated showing the intensity of the significance. In those cases where the null hypothesis could not be rejected, the α-level was not indicated.

6.4 Results and discussion

In Sections 6.4.1-6.4.5 *hypotheses* “*h*” are derived from each evaluation question and *methods* “*m*” for verifying these are described. For each hypothesis the *results* “*r*” are presented. For each evaluation question discussions are provided

6.4.1 Evaluation question I

Does SYCONDE clearly structure the solution path while designing connections?

SYCONDE describes the activities considered to be important for designing connections, hereinafter called *important activities*, and defines the order in which these activities should be used. It is expected that if no specific approach is used, connections will be designed by unsystematically using and repeating important and unimportant activities. For this reason it is assumed that designers working with SYCONDE, i.e. EDs, perform more of the important activities than designers working without SYCONDE, i.e. CDs. Through the holistic description of the important activities it is also assumed that EDs repeat each of these activities less often than CDs (hI-1). It is further assumed that EDs perceive to a higher level than CDs that their solution path was clearly structured (hI-2) and that they perceive SYCONDE as having supported them in structuring their solution path (hI-3).

Hypothesis hI-1

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, performs a larger number of important activities and repeats each of these less often.

Method mI-1

Table 6-1 lists the activities considered important and the related SYCONDE steps and shows how these are identified in the design processes of EDs and CDs; elements of SYCONDE are in italics and can be found in Chapter 5 and Appendix C. The activity ‘selection of connection concepts’ (step 7 of SYCONDE) is neither listed nor considered here because its utilisation depends amongst others on the number of connection concepts a designer perceives as large and thus conclusions cannot be directly drawn. Through analysis of the videotapes and the documentation produced by the designers, the number of the important activities performed and their repetitions were separately identified for each CD and ED. Observed activities that could not be allocated to the important ones were named and also documented. The performed number of important activities and their repetitions for the CG and EG are represented by the means of the values for the corresponding designers, i.e. CDs and EDs.

Table 6-1: Important activities, corresponding SYCONDE steps, and their identification

No.	**Important activities:**	**SYCONDE step:**	**Identification in the design process of EDs:**	**CDs:**
1	Consideration of component characteristics.	1. Preparation	Thinks aloud about the characteristics of the components to be assembled and their interfaces./ Completely fills in the *components scheme*.	Thinks aloud about:/ Makes notes about: characteristics of the components to be assembled and their interfaces.
2	Generation of a requirements list for the connection to be designed	2. Specifying connection requirements	Fills in the *requirements list*.	Documents the requirements.
3	Consideration of the existing locking technologies.	3. Rejecting unfeasible locking technologies	Thinks aloud about locking technologies./ Considers the *combination scheme* or the *locking technology list* with the intention to cancel unfeasible kinds of locking or locking technologies.	Thinks aloud about locking technologies./ Makes notes about the acceptation and cancellation of kinds of locking or locking technologies.
4	Consideration of the existing joining concepts.	4. Selecting/ generating joining concepts	Thinks aloud about varying the geometry of the component interfaces./ Enters sketches of joining concepts in the *combination scheme*.	Thinks aloud about:/ Makes notes about: varying the geometry of the component interfaces.
5	Generation of suitable combinations of locking technologies and joining concepts.	5. Combining locking technologies and joining concepts	Thinks aloud about possible combinations of kinds of locking or locking technologies and joining concepts./ Considers the *combination scheme* with the intention to tick suitable combinations of kinds of locking or locking technologies and joining concepts.	Thinks aloud about:/ Makes notes about: possible combinations of kinds of locking or locking technologies and the joining concepts specified before.
6	Consideration of geometrical connection characteristics.	6. Specifying connection concepts	Thinks aloud about the geometrical characteristics of the connection./ Fills in the *connection principles scheme*.	Thinks aloud about:/ Makes notes about: geometrical characteristics of the connection.
7	Consideration of locking methods and application to the components to be assembled.	8. Selecting/ generating locking methods	Thinks aloud about final solutions./ Fills in the *final solution form*.	Thinks aloud about final solutions./ Fills in the *final solution form*.
8	Evaluation of final solutions.	9. Evaluating the selected and generated final solutions	Thinks aloud about the fulfilment of the requirements through the achieved final solutions./ Fills in the *evaluation scheme*.	Thinks aloud about:/ Makes notes about: fulfilment of the requirements through the achieved final solutions.

Results rI-1

In Figure 6-1 the number of performed important activities and the total number of repetitions of these activities are shown for each CD, ED and the CG and the EG.

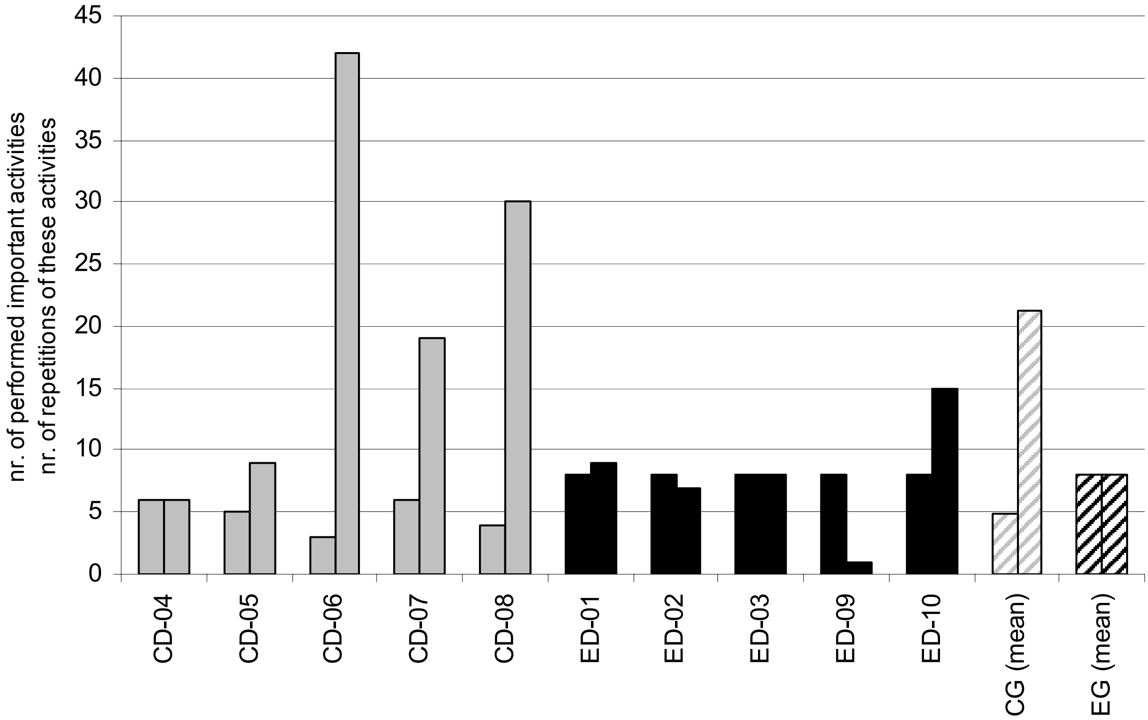


Figure 6-1: Number of performed important activities and their repetitions

All EDs performed all eight important activities. The EG therefore performed significantly more important activities than the CG with 4.8 performed important activities (U test, $\alpha=0.005$). As shown in Table 6-2 only some CDs performed the activities no. 1 to 4, no CD performed the activity no. 5 while all CDs performed the activities no. 6 to 8. With 8 repetitions the EG repeated the important activities non-significantly less often than the CG with 21.2 repetitions.

For identifying if the EG repeated particular important activities less often than the CG, each activity was analysed separately (Table 6-2).

Table 6-2: Performed important activities and their repetitions by the CG and the EG

No.	Activity:	SYCONDE step	Nr. performed		Nr. of repetitions	
			CG	EG	CG	EG
1	Consideration of component characteristics	1. Preparation	*2*	*5*	*0*	*0*
2	Generation of a requirements list for the connection to be designed	2. Specifying connection requirements	*3*	*5*	*2*	*3*
3	Consideration of existing locking technologies	3. Rejecting unfeasible locking technologies	*3*	*5*	*0*	*0*
4	Consideration of existing joining concepts	4. Selecting/ generating joining concepts	*1*	*5*	*1*	*5*
5	Generation of suitable combinations of locking technologies and joining concepts	5. Combining locking technologies and joining concepts	*0*	*5*	*0*	*4*
6	Consideration of geometrical connection characteristics	6. Specifying connection concepts	*5*	*5*	*29*	*17*
7	Consideration of locking methods and application to the components to be assembled	8. Selecting/ generating locking methods	*5*	*5*	*57*	*11*
8	Evaluation of final solutions	9. Evaluating the selected and generated final solutions	*5*	*5*	*17*	*0*
				total:	*106*	*40*
				mean:	*21.2*	*8*

In the corresponding significance test only those CDs having performed the particular activity were considered. The repetition of the activities no. 1, 3, 4 and 5 was not examined because activities no. 1 and 3 were repeated neither by the CG nor by the EG, activity no. 4 was performed only by one CD and activity no. 5 was not at all performed by the CG. Activity no. 2 was repeated three times by the EG and two times by the CG. However it was performed only by three CDs. The activities no. 6, 7 and 8 were repeated less frequently by the EG than by the CG. The U test (α=0.01) showed that of these only activity no. 7 was significantly less frequently repeated.

Hypothesis hI-1 cannot be confirmed because significance was only identified concerning the number of important activities performed and the repetition of activity nr 7. However, a tendency towards this hypothesis was observed.

Hypothesis hI-2

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, perceives to a higher level that the solution path was clearly structured.

Method mI-2

In Table 6-3, statements concerning the perceived level of structuring of the solution path, and the related ratings are given. For each statement the designers were asked to tick the most appropriate rating after they had finished the design task.

Table 6-3: Statements and ratings concerning the perceived structuring

Id.	Statements:	Ratings r:
a_{I-2}	My solution path was clearly structured.	not applicable at all: 0 rather not applicable: 1 neutral: 2 rather applicable: 3 fully applicable: 4
b_{I-2}	My solution path was rather unstructured.	

The level of structuring of the solution path perceived by each designer is represented through the median v_{I-2} of the numerical values of the ratings, i.e. $v_{I-2} = 0.5 * (r_{aI-2} + (4 - r_{bI-2}))$. The medians of the v_{I-2}-values of the corresponding designers, i.e. CDs and EDs, represent the level of structuring perceived by the CG and the EG.

Results rI-2

Figure 6-2 shows for the CDs, EDs, the CG and the EG the value representing the perceived level of structuring of the solution path. CD-04 stated not at all having perceived the solution path as structured. This is indicated through the value 0.

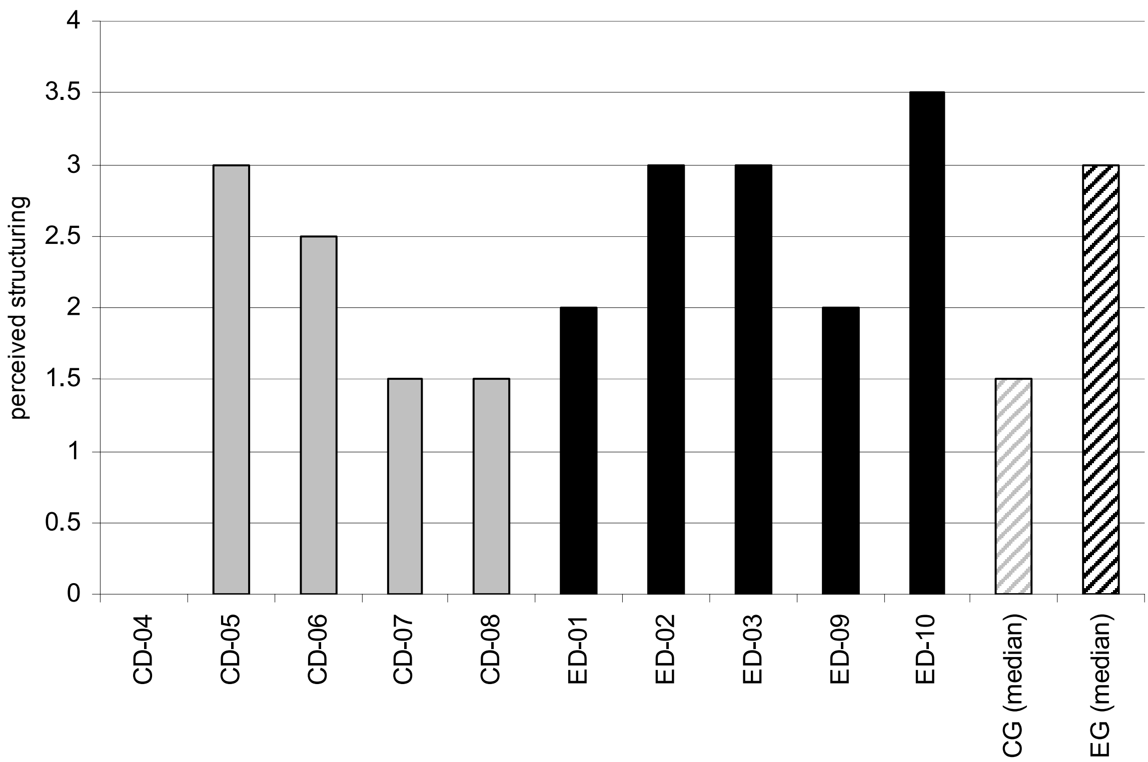


Figure 6-2: Perceived level of structuring of the solution path

Comparing the values of the EG, $v_{I-2,EG}$ = 3, and the CG, $v_{I-2,CG}$ = 1.5, the EG perceives to a non-significantly higher level than the CG that the solution path was clearly structured (U test). For this reason, hypothesis hI-2 cannot be confirmed.

Hypothesis hI-3

The group of designers working with SYCONDE, i.e. the EG, perceives SYCONDE as a support for structuring the solution path.

Method mI-3

In Table 6-4, a statement concerning the perceived support through SYCONDE for structuring the solution path, and the related ratings is given. The EDs were asked to tick the most appropriate rating after they had finished the design task.

Table 6-4: Statement and ratings concerning the perceived support of SYCONDE

Id.	Statement:	Ratings r:	
a_{I-3}	SYCONDE supported me in clearly structuring my solution path.	not applicable at all:	0
		rather not applicable:	1
		neutral:	2
		rather applicable:	3
		fully applicable:	4

The support each ED perceived is represented by the numerical value of the rating, i.e. a_{I-3}. The median of the EDs represents the support perceived by the EG.

Result rI-3

The EG perceives to have had some support of SYCONDE for structuring the solution path. Figure 6-3 shows that three designers (ED-01, -03, -10) perceive some and one designer (ED-02) full support. One designer (ED-09) perceives the support as neutral. This confirms hypothesis hI-3.

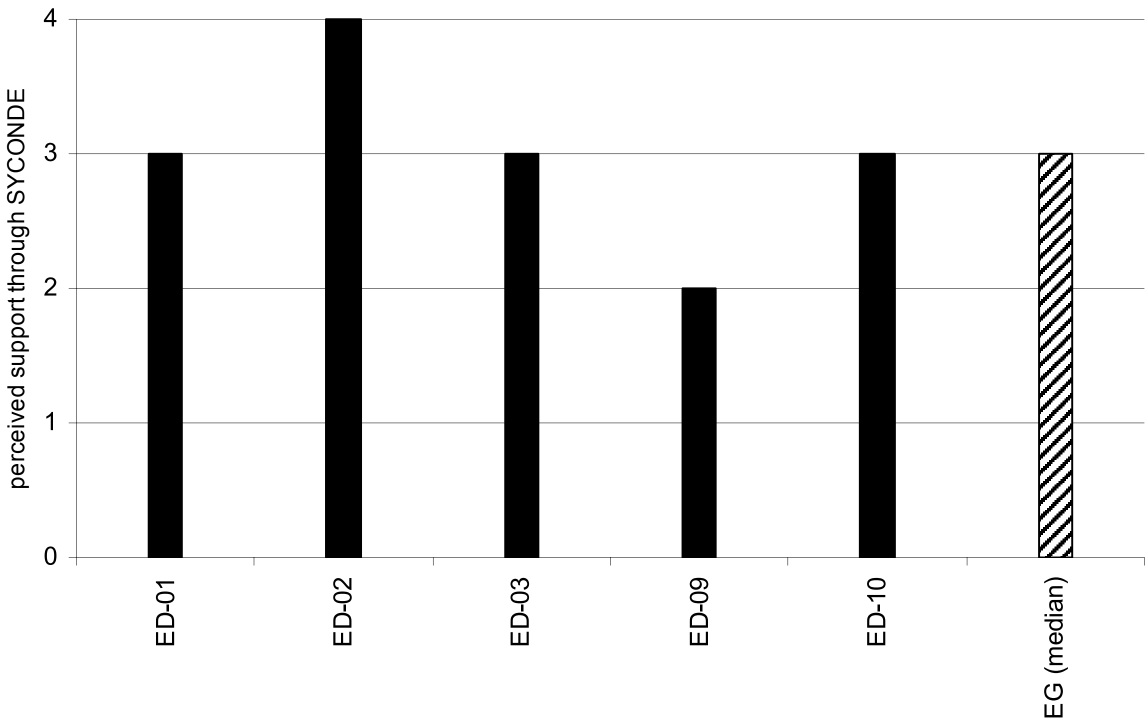


Figure 6-3: Perceived support of SYCONDE for structuring the solution path

Discussion

That all EDs performed all important activities shows that they used SYCONDE throughout.

The repetitions of activities by the EDs might generally occur due to the fact that the EDs used SYCONDE for the first time and thus were not familiar with it. Also, SYCONDE is in English so that the designers might not have completely understood particular steps and for this reason repeated these. The repetition of activity no. 4 can also be because of complexity. Three EDs complained about the complexity of the corresponding SYCONDE step.

The low number of repetitions of activities no. 6 and 7 by the EG in relation to the CG might result from SYCONDE, i.e. the preparation in step 4 and 5 and the supportive information. As can be seen in Table 6-2, activity no. 4 was performed only by one CD and activity no. 5 by none of the CG.

Three of five EDs perceived their solution path to be structured. The diagrams with the order of performed steps observed in the design processes (Appendix D.3) show that the solution path of all EDs was more structured than that of the CDs. For the EDs the diagrams result in patterns similar to a stair profile moving gradually from activity no. 1 to 8 while the patterns of the CDs look more like a saw-tooth jumping back and forth focusing on the activities no. 6, 7 and 8.

Within the EG the following observations were made:

- Activity no. 11, i.e. the introduction and discussion of SYCONDE, was done only once by all EDs.
- While three of five EDs (ED-02, -09 and -10) read the problem description and drawings, i.e. activity no. 12, only once, two EDs (ED-01 and -03) read the problem description and drawings more frequently.

It is assumed that the problem description was read again, when there came up a lack of idea within an activity. Apparently this happened to ED-01 and -03, because they worked in less design projects and had less experience in designing connections than ED-02, -09 and -10. While ED-02 and -10 worked in about fifteen design projects, ED-01 and -03 worked in about eight. ED-09 and -10 designed a connection within the last twelve months; ED-03 did not do this within this period.

- All EDs jumped between the following activities:

  no. 9, i.e. the selection of combinations of joining concepts and locking technologies;

  no. 6, i.e. the consideration of geometrical connection characteristics;

  no. 7, i.e. the consideration of locking methods and application to the components to be assembled.

These jumps are related to the fact that for the selection process, i.e. activity no. 9, the combinations must be taken from the connection principle scheme realised in activity no. 6. For continuing with activity no. 7, the selected combinations must be taken from the selection chart realised in activity no. 9.

- Four of five EDs (ED-01, -02, -03, -09) jumped from other activities than activity no. 9 to activities already done before.

ED-01 jumped from the consideration of geometrical connection characteristics, i.e. activity no. 6, to the generation of suitable combinations of locking technologies and joining concepts, i.e. activity no. 5, and further to the consideration of existing joining concepts, i.e. activity no. 4. Apparently ED-01 had problems with determining suitable joining and connection concepts. This assumption was confirmed through the questionnaire in which ED-01 stated difficulties with step 4 as one of the most negative experiences during working on the design task. ED-10 jumped back from the consideration of locking methods and application to the components to be assembled, i.e. activity no. 7, to the consideration of existing joining concepts, i.e. activity no. 4 and then performed again activities no. 5, 6 and 7. This was caused to the fact that ED-10 got ideas for further solution variants and realised these by iteration. The remaining repetitions observed could mainly be traced back to the fact that the designers were not familiar with the steps of SYCONDE.

CDs performed important activities in some cases in an uncommon order. This was identified by the following observations:

- Two of five CDs (CD-06 and -08) did not prepare a requirements list, i.e. activity no. 2. They directly started with considering and applying locking methods, i.e. activity no. 7.
- Three CDs (CD-05, CD-06 and -08) did not explicitly consider the component characteristics, i.e. activity no. 1.
- One CD (CD-08) did not explicitly consider the existing kinds of locking or locking technologies, i.e. activity no. 3. Two CDs (CD-05 and -06) did not do this until they had no further idea concerning the consideration and application of locking methods, i.e. activity no. 7. Due to the fact that CDs worked without SYCONDE, they did not use the lists with locking technologies and locking methods.
- Three CDs (CD-05, -06 and -08) evaluated the quality of their final solutions, i.e. activity no. 8, separately in several steps instead of comparatively in one step.

The differences in the CG are ascribed to different expertises of the CDs. CD-04, -05 and -07 worked more systematically than CD-06 and -08. CD-04 and CD-07 had worked in about ten design projects, CD-05 stated to have some knowledge of connection techniques and some experience in designing connections. CD-06 stated to have some experience in connection techniques, CD-08 stated to have some experience in designing connections.

CDs further performed some steps differently to EDs:

- While only two EDs (ED-01 and -03) read the problem description/drawings more than once, this was done by four CDs (CD-04, -05, -07 and -08).
- Thinking or brooding and reading the problem description or the drawings was more frequently done by CDs than by EDs.

It is assumed that CDs thought, brooded and read the problem description/drawing when the next action was not clear and needed to be defined. CDs might have done this more frequently than EDs, because for them the actions to be done are not prescribed as this is the case for the EDs.

Designers perceived at least neutral support of SYCONDE for structuring their design process. However, four of five designers stated that the structured process was an advantage of SYCONDE.

6.4.2 Evaluation question II

Does SYCONDE support designers in considering a large solution space while designing connections?

SYCONDE provides the solution space of connection characteristics. For this reason it is assumed that designers working with SYCONDE, i.e. EDs, consider a larger solution space and hence more solution variants in the important activities than designers working without SYCONDE, i.e. CDs, (hII-1). It is further assumed that EDs perceive to a higher level than CDs that they have considered a large solution space (hII-2) and that they perceive SYCONDE as having supported them in considering a large solution space (hII-3).

Hypothesis hII-1

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, considers more solution variants in the important activities.

Method mII-1

In Table 6-5 solution categories are allocated to each important activity and SYCONDE step. The number of solution variants considered in each solution category is identified for each CD and ED through analysis of the videotapes and the documentation produced by the designers. The value representing the number of solution variants considered by the CG and the EG in each solution category is the mean of the number considered by the corresponding designers, i.e. CDs and EDs.

Table 6-5: Important activities, SYCONDE steps and solution categories

Activity:	SYCONDE step no.:	Solution category: No.:	Solution:
Consideration of the existing locking technologies.	3: Rejecting unfeasible locking technologies	1	Locking technologies
Consideration of the existing joining concepts.	4: Selecting/ generating joining concepts	2	Joining concepts
Generation of suitable combinations of locking technologies and joining concepts.	5: Combining locking technologies and joining concepts	3	Combination of locking technologies and joining concepts
Consideration of geometrical connection characteristics.	6: Specifying connection concepts	4	Connection principles
Consideration of locking methods and application to the components to be assembled.	8: Selecting/ generating locking methods	5	Locking methods

Results rII-1

Figure 6-4 shows the number of solution variants considered in each solution category by the CDs, EDs, the CG and EG.

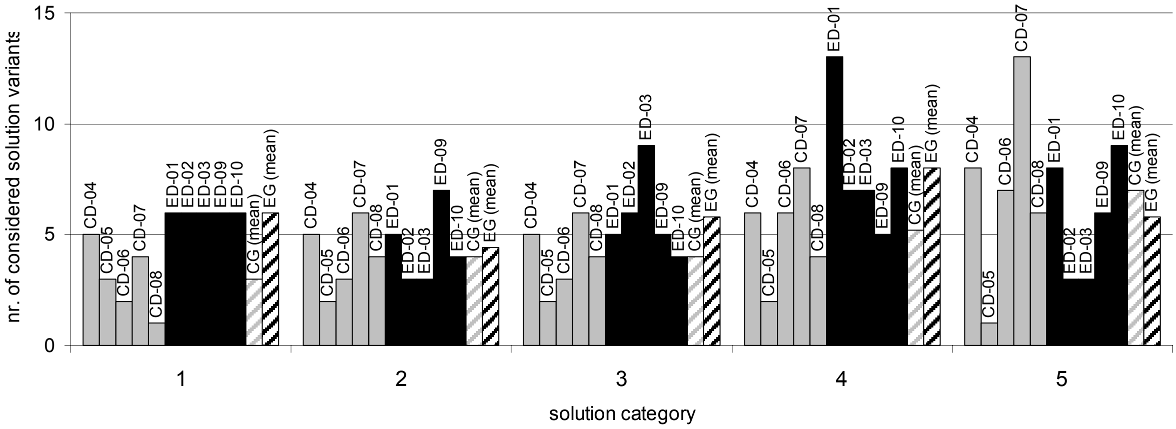


Figure 6-4: Number of solution variants considered in each solution category

In Table 6-6 the total number of solution variants considered by the CG and the EG in each solution category are listed.

Table 6-6: Total numbers of solutions variants considered by the CG and EG

Solution category		Total number of considered solution variants	
No.:	**Solution:**	**CG**	**EG**
1	locking technologies	15	30
2	joining concepts	20	22
3	combinations of locking technologies and joining concepts	20	29
4	connection principles	26	40
5	locking methods	35	29
total:		116	150

In solution category 5, i.e. locking methods, the EG considered non-significantly less solution variants than the CG (U test). In all other solution categories the EG considered more solution variants than the CG. The U test ($\alpha = 0.01$) found only for solution category 1, i.e. locking technologies, that the EG considered significantly more solution variants than the CG. Hence, hypothesis hII-1 cannot be confirmed.

Hypothesis hII-2

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, perceives to a higher level that a large solution space is considered.

Method mII-2

In Table 6-7, statements concerning the perceived size of the considered solution space, and the related ratings are given. For each statement the designers were asked to tick the most appropriate rating after they had finished the design task.

Table 6-7: Statements and ratings concerning the perceived solution space

Id.	Statements:	Ratings r:
a_{II-2}	I have the feeling I have considered a large solution space.	not applicable at all: 0 rather not applicable: 1 neutral: 2 rather applicable: 3 fully applicable: 4
b_{II-2}	I have the feeling I have considered a small solution space.	

The size of the considered solution space perceived by each designer is represented by the median v_{II-2} of the numerical values of the ratings, i.e. $v_{II-2} = 0.5 * (r_{aII-2} + (4 - r_{bII-2}))$. The medians of the v_{II-2}-values of the corresponding designers, i.e. CDs and EDs, represent the size of the considered solution space perceived by the CG and EG.

Results rII-2

Figure 6-5 shows for the CDs, EDs, the CG and EG the perceived size of the considered solution space.

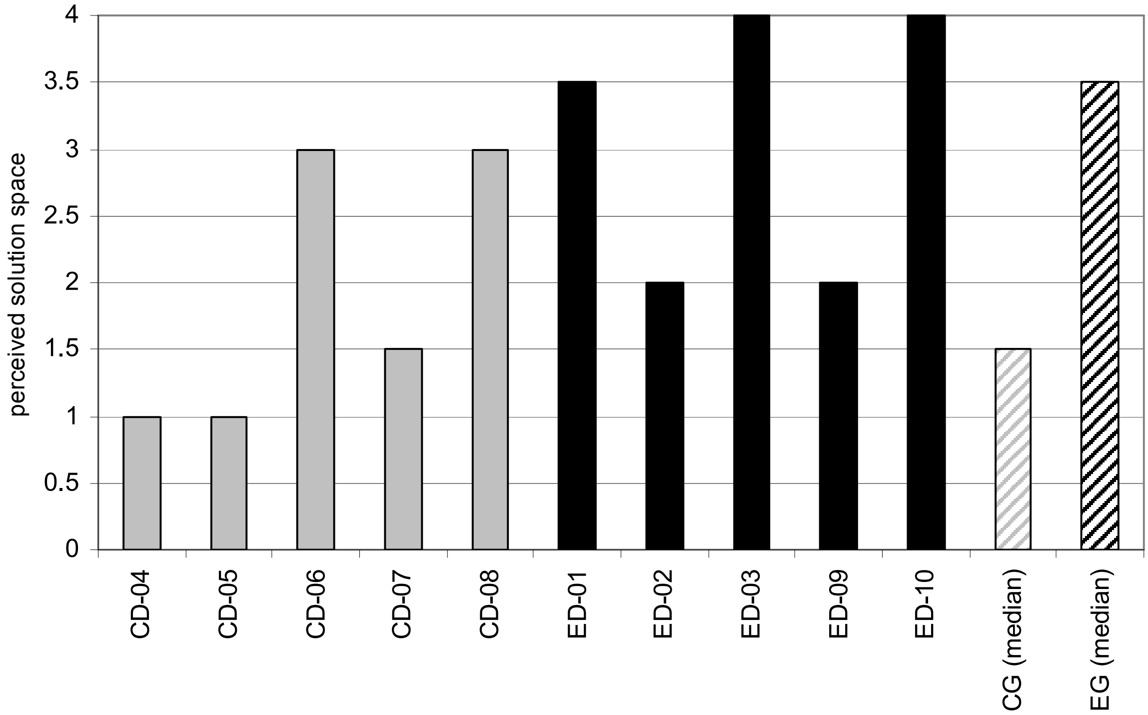


Figure 6-5: Perceived seize of the considered solution space

Comparing the values of the CG, $v_{II-2, CG} = 1.5$, and the EG, $v_{II-2, EG} = 3.5$, the EG perceives to a non-significantly higher level than the CG that the considered solution space was large (U test). For this reason, the hypothesis hII-2 cannot be confirmed.

Hypothesis hII-3

The group of designers working with SYCONDE, i.e. the EG, perceives SYCONDE as a support for considering a large solution space.

Method mII-3

In Table 6-8, a statement concerning the perceived support through SYCONDE for considering a large solution space, and the related ratings are given. The EDs were asked to tick the most appropriate rating for this statement after they had finished the design task.

Table 6-8: Statement and ratings concerning the perceived support through SYCONDE

Id.	Statement:	Ratings r:	
a_{II-3}	SYCONDE supported me in considering a large solution space	not applicable at all:	0
		rather not applicable:	1
		neutral:	2
		rather applicable:	3
		fully applicable:	4

The support each ED perceived is represented by the numerical value of the rating, i.e. a_{II-3}. The median of the EDs represents the support perceived by the EG.

Results rII-3

The EG perceives to have had some support of SYCONDE for considering a large solution space. Figure 6-6 shows that three designers (ED-01, -02, -09) perceive some and two designers (ED-03, -10) full support. This confirms the hypothesis hII-3.

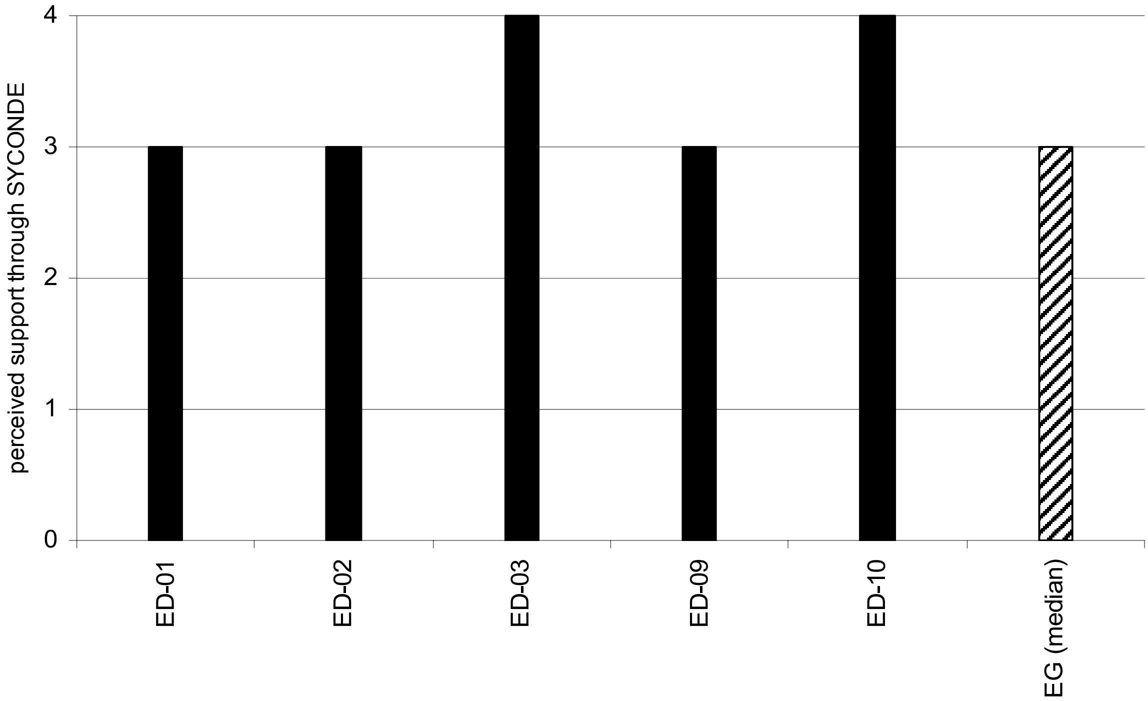


Figure 6-6: Perceived support of SYCONDE for considering a large solution space

Discussion

The reason that the CG considered more solution variants for solution category 5, i.e. locking methods, than the EG might be that CDs were mainly focused on solution variants for locking methods directly to be applied to the components to be connected, while EDs aimed to achieve solution variants for all solution categories. With this, the CG could have an advantage compared to the EG if an easy connection task can anyhow be quickly solved. However, it is assumed that the EG will provide more connection variants for the easy task, and be better prepared to solve difficult tasks.

ED-01, -03 and -10 had the perception of having considered a large solution space but only ED-03 and -10 perceived that this was fully supported by SYCONDE, while ED-01 perceived only some support. It is assumed that ED-01 perceived less support of SCONDE, because of the problems with step 4, i.e. selecting/generating joining concepts, ED-01 stated in the questionnaire as one of the most negative experiences during working on the design task (see also Discussion in Section 6.4.1).

6.4.3 Evaluation question A

Does SYCONDE support designers in their design processes?

SYCONDE is developed to guide designers through the design process of connections, to indicate the solution space of working principles and geometrical characteristics of connections and to support the documentation of the results. For this reason it is assumed that designers working with SYCONDE, i.e. EDs, experience less effort in the process of designing connections than designers working without SYCONDE, i.e. CDs (hA-1). It is further assumed that EDs perceive SYCONDE as a support for designing connections (hA-2).

Hypothesis hA-1

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, experiences less effort in the process of designing connections.

Method mA-1

Directly before starting to work on the design task and then every ten minutes the CDs and EDs were asked to tick the actually experienced effort on the Eiler scale (Figure 6-7) allocating different effort intensities to interval scaled values between 0, i.e. no effort, and 220, i.e. highest effort [Eilers et al.-85].

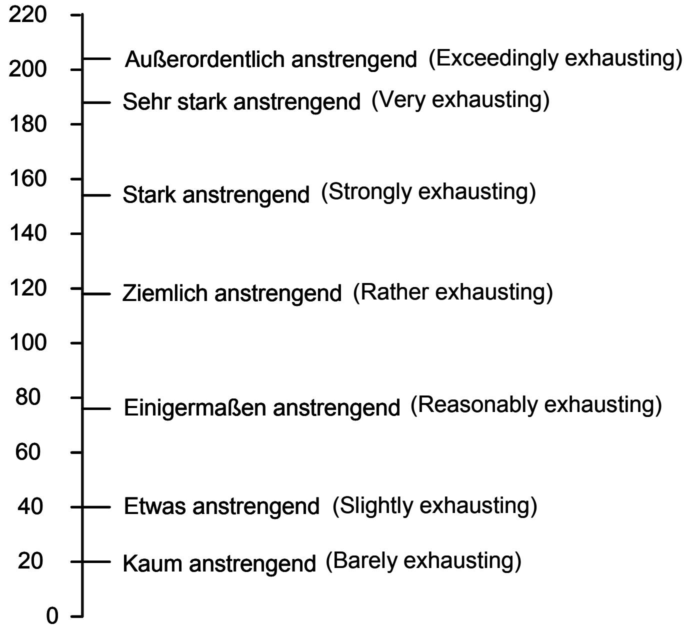


Figure 6-7: Effort scale of Eilers [Eilers et al.-85]

The effort “e” each designer experiences over the whole design process is represented by the mean of the first value e_0, i.e. the value ticked before starting to work on the design task, and the highest value of those ticked during the design process, e_{max}, i.e. $e = 0,5 * (e_{max} - e_o)$ [Eilers et al.-85]. The means of the efforts of the corresponding designers, i.e. CDs and EDs, represent the efforts perceived by the CG and the EG.

Results rA-1

Figure 6-8 shows the efforts CDs, EDs, and the CG and EG experienced over the whole design process.

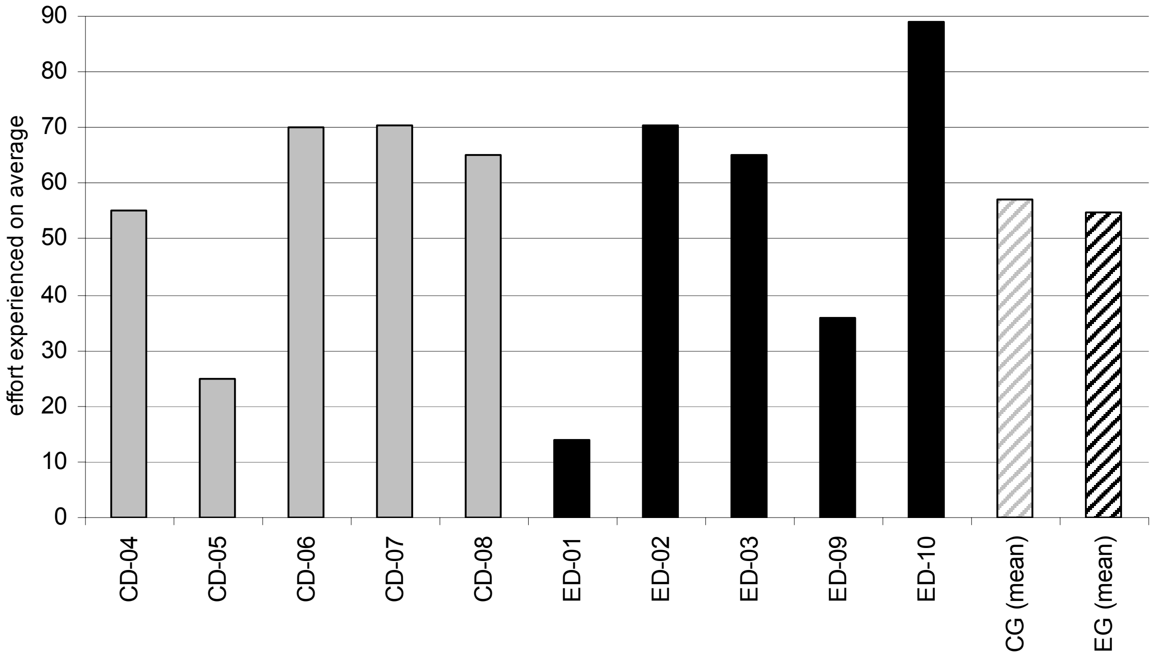


Figure 6-8: Effort experienced over the whole design process (highest possible value: 220)

With 54.9 on the Eilers scale the EG experiences non-significantly less effort than the CG with 57.1 (U test). For this reason, hA-1 cannot be confirmed.

Hypothesis hA-2

The group of designers working with SYCONDE, i.e. the EG, perceives SYCONDE as a support for designing connections.

Method mA-2

In Table 6-9 statements concerning the perceived support through SYCONDE for designing connections, and the related ratings are given. For each statement, the EDs were asked to tick the most appropriate rating after they had finished the design task.

Table 6-9: Statements and ratings concerning the perceived support through SYCONDE

Id.	Statements:	Ratings r:
a_{A-2}	I have the feeling that SYCONDE supported me in designing connections.	not applicable at all: 0 rather not applicable: 1 neutral: 2 rather applicable: 3 fully applicable: 4
b_{A-2}	I have the feeling that SYCONDE did not support me in designing connections.	

The support each ED perceived is represented by the median v_{A-2} of the numerical values of the ratings, i.e. $v_{A-2} = 0.5 * (r_{aA-2} + (4 - r_{bA-2}))$. The median of the EDs represents the support perceived by the EG.

Result rA-2

The EG perceives to have had some support of SYCONDE for designing connections. Figure 6-9 shows that three designers (ED-01, -02, -10) perceive some and one designer (ED-03) full support. One designer (ED-09) perceives neutral support. This confirms the hypothesis hA-2.

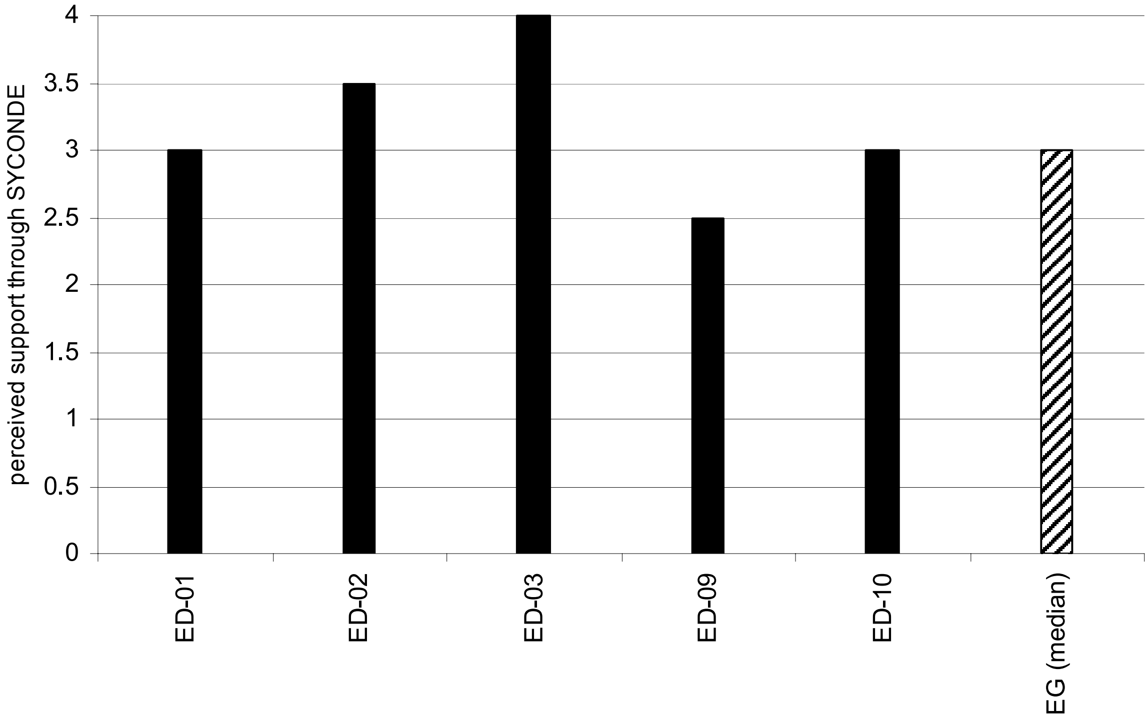


Figure 6-9: Perceived support of SYCONDE for designing connections

Discussion

The efforts experienced by the EDs differ more between each other than those of the CDs. This might be due to the fact that SYCONDE is in English and the EDs might have experienced different efforts in understanding the text. Another reason might be that EDs used SYCONDE for the first time and some might have required more effort for familiarising themselves than others. This is confirmed by the fact that four of five EDs (ED-01, -02, -03 and -10) stated the necessity of training as a disadvantage of SYCONDE. However, the same designers perceived SYCONDE at least as providing some support for designing connections.

6.4.4 Evaluation question B

Does SYCONDE increase the effectiveness of the process of designing connections?

Through SYCONDE connection characteristics and resulting properties are considered. For this reason it is assumed that designers working with SYCONDE, i.e. EDs, are more effective, i.e. realise final solutions with higher quality and suitability for the design task, than designers working without SYCONDE, i.e. CDs (hB-1). It is further assumed that EDs are to a higher level content with the quality of their final solutions than CDs (hB-2) and that they perceive SYCONDE as a contribution to their full satisfaction with the quality of their final solutions (hB-3).

Hypothesis hB-1

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, achieves final solutions with higher quality and higher suitability for the design task.

Method mB-1

In the following, the quality of a final solution and the suitability of a final solution for the design task are considered separately. The quality of a final solution is represented through an absolute quality value only relating on the fulfilment of the requirements given in the design task. The suitability of a final solution for the given design task is represented in relation to all final solutions.

Quality values were determined for all final solutions by assessing the fulfilment of the requirements given in the design task (Appendix D.1) using the marks '0', '1' and '2'. Table 6-10 shows the meaning of the marks for each requirement.

Table 6-10: Marks and their meaning for each requirement

	Marks for indicating the fulfilment:		
Requirement:	**0**	**1**	**2**
The shape of the components to be assembled should not be changed.	Geometrical change is necessary on both components.	Geometrical change is necessary on one of the components.	No geometrical change is necessary on the components.
(Dis)assembly should be easy, reversible and to be realised with as few separate parts as possible.	At least two of the following properties apply: Tools are necessary. (Dis)assembly is not reversible. Additives are necessary.	Tools are necessary. or (Dis)assembly is not reversible. or Additives are necessary.	No tool is necessary. and (Dis)assembly is reversible. and No additive is necessary.
Connection should prevent clearance and loss of preload.	The probability of clearance or loss of preload is high.	The probability of clearance or loss of preload is medium.	The probability of clearance and loss of preload is very low.

The sum of the marks given for each requirement is the quality value of a final solution. A resulting quality value of 0 represents the lowest, a value of 6 the highest fulfilment of the quality criteria. The quality value achieved by each CD and ED is represented by the mean of the quality values of each of their final solutions. The quality value achieved be the CG and EG is calculated in the same way.

The suitability for the design task was determined through assuming for each final solution the long-term maintenance of its connective function for the given task. To determine the relative suitability, pairwise comparison, a method for assessing findings in relation to each other [Bortz & Döring-06, pp. 157], was used. So as not to change the order determined by the quality values, only solutions with the same quality values were assessed in relation to each other. This is illustrated in Figure 6-10 by the pairwise comparison matrix for final solutions with quality value 0. Final solutions are labelled using the designer identifier and the solution number, e.g. ED-01 – 12 = 12th solution of designer ED-01. Pairwise, each final solution in the column was compared with each final solution in the row concerning the long-term maintenance of its connection function for the design task. The results were documented in the corresponding cells of the matrix using ‘+’, if the final solution in the column promised a better long-term maintenance of the connection function, and ‘0’, if this was not the case.

quality value: 0	ED-01 - 12	ED-01 - 13	CD-06 - 2	CD-08 - 2	ED-09 - 9
ED-01 - 12	-	0	0	+	+
ED-01 - 13	0	-	0	+	0
CD-06 - 2	0	0	-	+	+
CD-08 - 2	0	0	0	-	0
ED-09 - 9	0	0	0	+	-

Figure 6-10: Pairwise comparison matrix for final solutions with quality value of 0

For bringing the suitability of each final solution in a ranking, the pairwise comparison matrices were transformed into dominant matrices. This is realised by replacing each ‘+’ by ‘1’ while ‘0’ remains ‘0’. Figure 6-11 shows the dominant matrix for the final solutions with quality value 0 derived from Figure 6-10. The sum resulting from totalling a row is the suitability value representing the suitability of the final solution in the first column in relation to all final solutions with the same quality value. A high value represents high suitability. All final solutions were ranked such that the order determined by the quality value was not changed, i.e. final solutions with a quality value of 0 could not get a higher suitability rank than those with a quality value of 1. This was realised in two steps, the preliminary and the final ranking [Bortz & Döring-06, p. 155]. In the preliminary ranking all final solutions were ranked through whole numbers (Figure 6-11) whereby each rank was provided only once. This results in different ranks for final solutions with the same suitability value. In the final ranking all of these were substituted through a tie, i.e. the mean of all preliminary ranks with the same suitability value (Figure 6-11). Thus, besides allocating identical ranks to final solutions with identical suitability, the final ranking also represents the distances between the particular final solutions within the ranking.

quality value: 0	ED-01 - 12	ED-01 - 13	CD-06 - 2	CD-08 - 2	ED-09 - 9	Σ	preliminary ranking	final ranking
CD-08 - 2	0	0	0	-	0	0	1	1
ED-01 - 13	0	-	0	1	0	1	2	2.5 (tie for 2 + 3)
ED-09 - 9	0	0	0	1	-	1	3	2.5 (tie for 2 + 3)
ED-01 - 12	-	0	0	1	1	2	4	4.5 (tie for 4 + 5)
CD-06 - 2	0	0	-	1	1	2	5	4.5 (tie for 4 + 5)

Figure 6-11: Dominant matrix and ranking of final solutions with a quality value of 0

The medians of the suitability ranks of the corresponding final solutions represent the ranks of the CDs, EDs, the CG and the EG concerning the suitability of their final solutions for the design task.

Result rB-1

Figure 6-12 gives an overview of the number of final solutions realised by each designer.

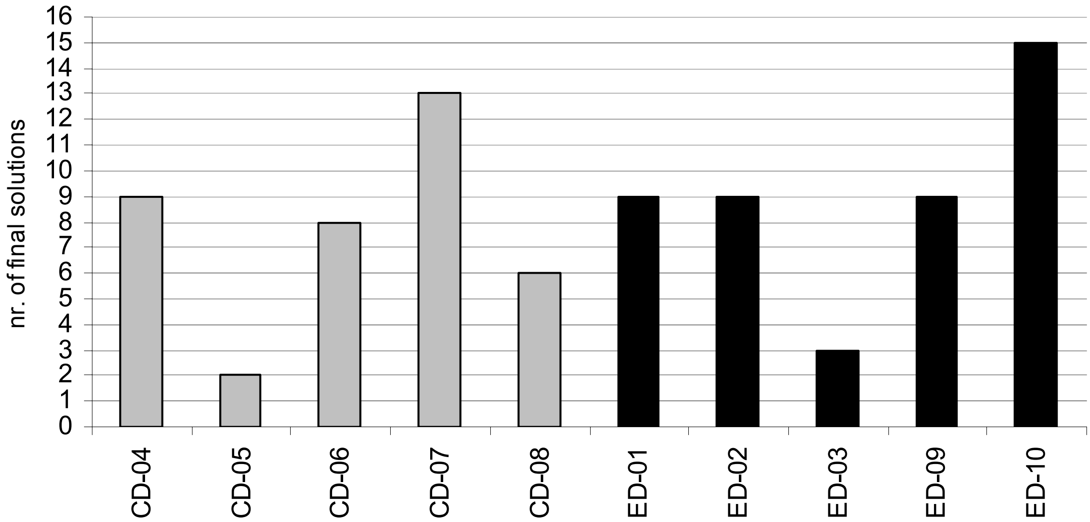


Figure 6-12: Number of final solutions realised by the designers

Figure 6-13 shows the quality values each CD, ED, CG and EG achieved with the final solutions.

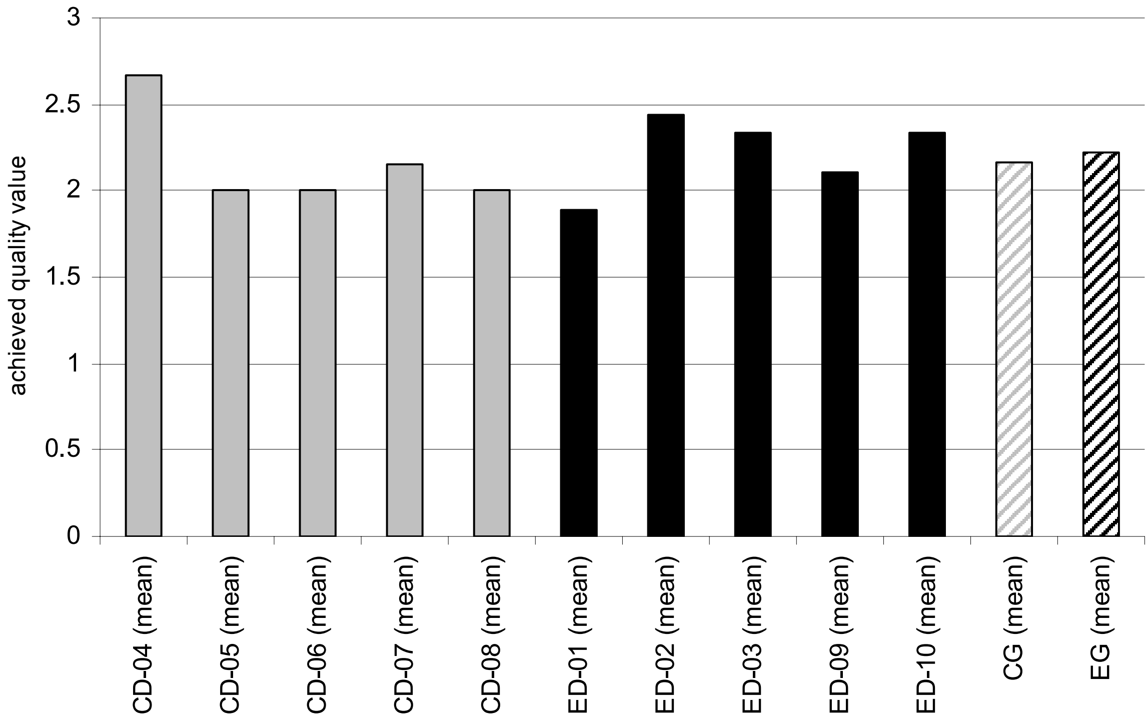


Figure 6-13: Quality values of the final solutions of designers and groups (highest possible value = 6)

With a quality value of 2.22, the solutions of the EG have a non-significantly higher quality than those of the CG with a quality value of 2.16 (U test).

Figure 6-14 shows the suitability rank each CD, ED, CG and EG achieved with the final solutions.

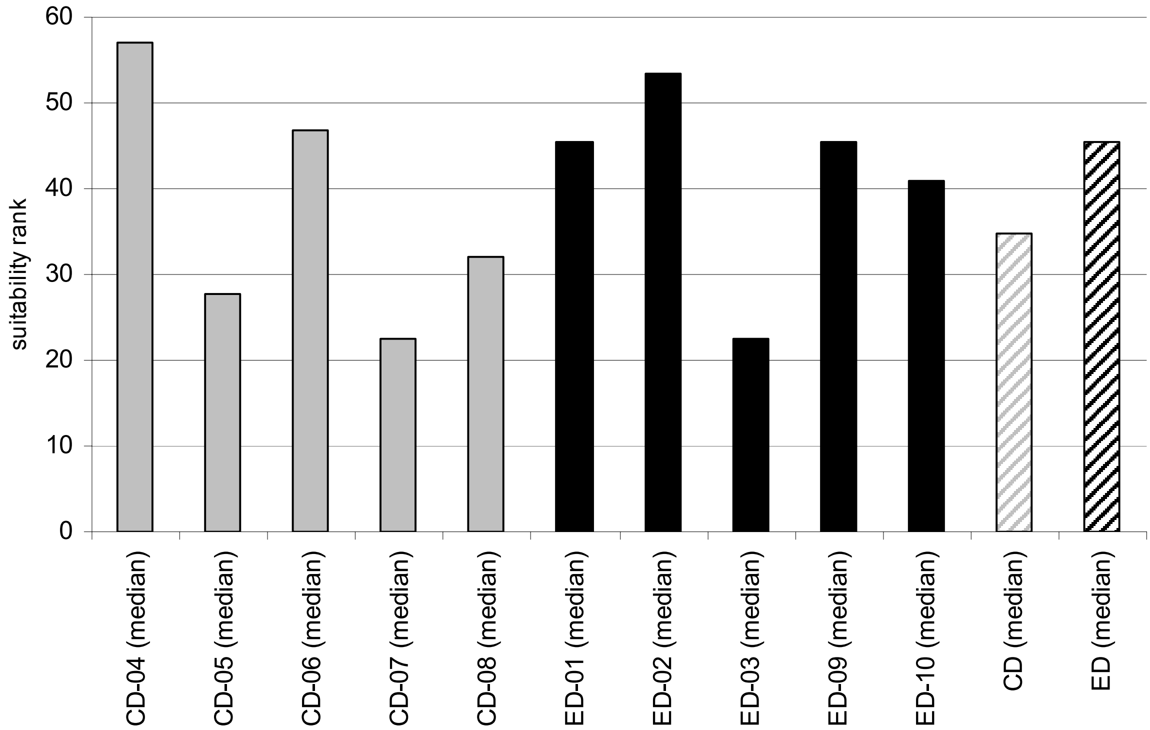


Figure 6-14: Suitability ranks of the final solutions of designers and groups

With 45.5, the EG achieves a non-significantly higher suitability rank than the CG with 34.75 (U test).

Hypothesis hB-2 cannot be confirmed because the EG achieved only a non-significantly higher quality value and suitability rank than the CG.

Hypothesis hB-2

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, is to a higher level content with the quality of the final solutions.

Method mB-2

In Table 6-11 statements concerning the contentment with the quality of the final solutions, and the related ratings are given. For each statement the designers were asked to tick the most appropriate rating after they had finished the design task.

Table 6-11: Statements and ratings concerning the contentment with the quality

Id.	Statements:	Ratings r:
a_{B-2}	I am fully content with the quality (includes also the fulfilment of the requirements) of my final solutions.	not applicable at all: 0 rather not applicable: 1 neutral: 2
b_{B-2}	I am not content with the quality (includes also the fulfilment of the requirements) of my final solutions.	rather applicable: 3 fully applicable: 4

The level of contentment with the quality of the final solutions perceived by each designer is represented through the median v_{B-2} of the numerical values of the ratings, i.e. $v_{B-2} = 0.5 * (r_{aB-2} + (4 - r_{bB-2}))$. The medians of the v_{B-2}-values of the corresponding designers, i.e. CDs and EDs, represent the level of contentment perceived by the CG and the EG.

Results rB-2

Figure 6-15 shows for the CDs, EDs as well as the CG and the EG the level of contentment with the quality of their final solutions.

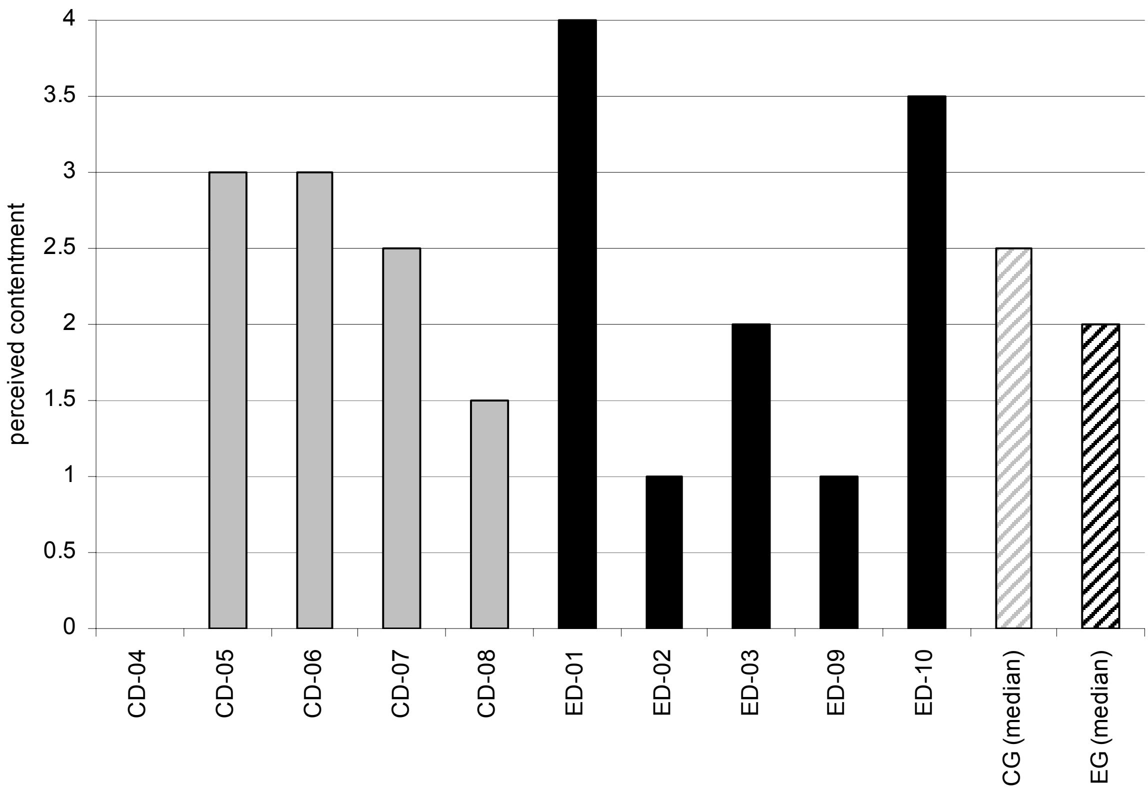


Figure 6-15: Level of contentment with the quality of the final solutions

Comparing the values of the EG, $v_{B-2, \text{median EDs}} = 2$, and the CG, $v_{B-2, \text{median, CDs}} = 2.5$, the EG is to a non-significantly lower level content with the quality of their final solutions than the CG (U test). This rejects hB-2.

Hypothesis hB-3

The group of designers working with SYCONDE, i.e. the EG, perceives SYCONDE as a contribution to full satisfaction with the quality of the final solutions.

Method mB-3

In Table 6-12 a statement concerning the perceived contribution of SYCONDE to full satisfaction with the quality of the final solutions, and related ratings are given. The EDs were asked to tick the most appropriate rating for this statement after they had finished the design task.

Table 6-12: Statement and ratings concerning the perceived contribution of SYCONDE

Id.	Statement:	Ratings r:	
a_{B-3}	SYCONDE was a contribution to full satisfaction with the quality (includes also the fulfilment of requirements) of my final solutions.	not applicable at all:	0
		rather not applicable:	1
		neutral:	2
		rather applicable:	3
		fully applicable:	4

The contribution to full satisfaction with the quality of the final solutions each ED perceived through SYCONDE is represented by the numerical value of the rating, i.e. a_{B-3}. The median of the EDs represents the contribution perceived by the EG.

Result rB-3

The EG perceives neutral contribution of SYCONDE to full satisfaction with the quality of the final solutions.Figure 6-16 shows that two designers (ED-01, -03) perceive some, two others (ED-02, -10) neutral, and one (ED-09) rather no contribution. This rejects the hypothesis hB-3.

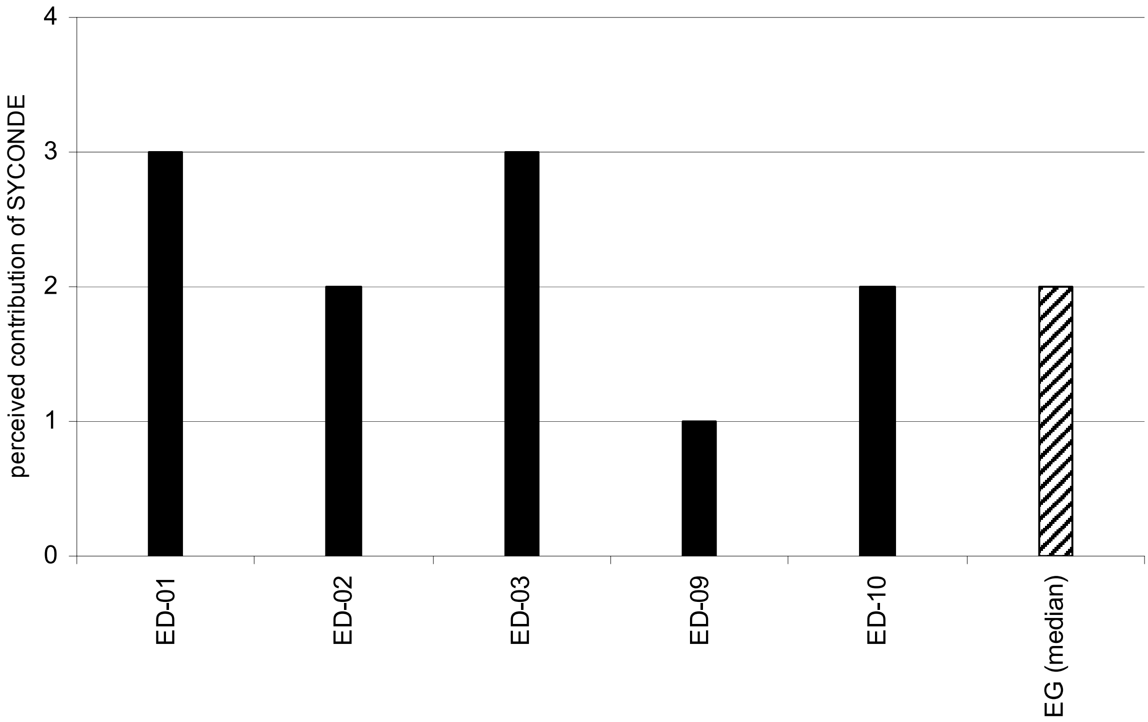


Figure 6-16: Perceived contribution of SYCONDE to full satisfaction with the final solutions

Discussion

While the quality values achieved by CDs and EDs are similar, four of five EDs (ED-01, -02, -09 and -10) achieved a suitability rank higher than 40. This was realised by only two of five CDs (CD-04 and -06).

The level of contentment with the quality of the final solutions neither relates for the EDs nor for the CDs with their achieved quality values (Figure 6-13) and suitability ranks (Figure 6-14). For example, CD-04 achieved the highest quality value and suitability rank but stated not being content with the quality of the realised final solutions (value = 0 in Figure 6-15). Remarkable is that ED-02 and -09 achieved the highest suitability ranks of the EG but stated the lowest contentment with the quality of their final solutions. The reason that the EG was to a lower level content with the quality of the realised final solutions might be that EDs became aware of the large solution space by using SYCONDE and questioned whether their final solutions covered this space. A comparison between Figure 6-15, i.e. level of contentment with the quality of the final solutions, and Figure 6-5, i.e. perceived seize of the considered solution space, confirms that those designers perceiving that their considered solution space was large (ED-01, -03, -10) were to a higher level content with the quality of their final solutions than those designers who did not perceive that their considered solution space was large (ED-02 and -09).

Three of five designers (ED-02, -09 and -10) perceived neutral or no contribution of SYCONDE to full satisfaction with the final solutions and complained that the approach required too much knowledge about connections (ED-02), that the design process was structured too much (ED-09) and that the joining and connection concepts were complex (ED-10). ED-01 was to a high level content with the quality of the final solutions and perceived some contribution of SYCONDE to full satisfaction with the final solutions. A comparison between Figure 6-16, i.e. perceived contribution of SYCONDE to full satisfaction with the final solutions, and *Figure 6-3*, i.e. perceived support of SYCONDE for structuring the solution path, shows that two EDs (ED-01, -03) perceived through SYCONDE constant support concerning both aspects, i.e. full satisfaction with the final solutions and structuring of the solution path, while three EDs (ED-02, -09 and -10) perceived through SYCONDE a higher support for structuring the solution path than for contributing to full satisfaction with the final solutions.

6.4.5 Evaluation question C

Does SYCONDE increase the efficiency of the process of designing connections?

It is assumed that SYCONDE supports designers such that those working with SYCONDE, i.e. EDs, achieve in the same time more final solutions with a higher quality and hence are more efficient than designers working without SYCONDE, i.e. CDs (hC-1). It is further assumed that EDs perceive to a higher level than CDs that they have worked efficiently (hC-2) and that they perceive SYCONDE as having supported them in working efficiently (hC-3).

Hypothesis hC-1

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, is more efficient.

Method mC-1

The efficiency of each designer is determined through the efficiency rate r_{eff}, i.e. the product of the quality value determined in Section 6.4.4 and the number of final solutions achieved per hour: $r_{eff,\ CD,\ ED}$ = quality value$_{CD,\ ED}$ * number of final solutions per hour$_{CD,\ ED}$.

The number of final solutions each designer achieved per hour is the quotient of the total number of realised final solutions and the total design time. The total design time is derived from the time taken at the beginning and end of the design process as well as at the beginning and end of breaks. The mean of the number of final solutions achieved per hour by the corresponding designers, i.e. CDs and EDs, represents the number of final solutions achieved per hour by the CG and EG.

The efficiency rate of the CG and EG is the product of the corresponding quality value determined in Section 6.4.4 and the number of final solutions achieved per hour, i.e. $r_{eff,\ CG,\ EG}$ = quality value$_{CG,\ EG}$ * number of final solutions per hour$_{CG,\ EG}$.

Results rC-1

Figure 6-17 shows the number of final solutions CDs, EDs, the CG and the EG achieved per hour.

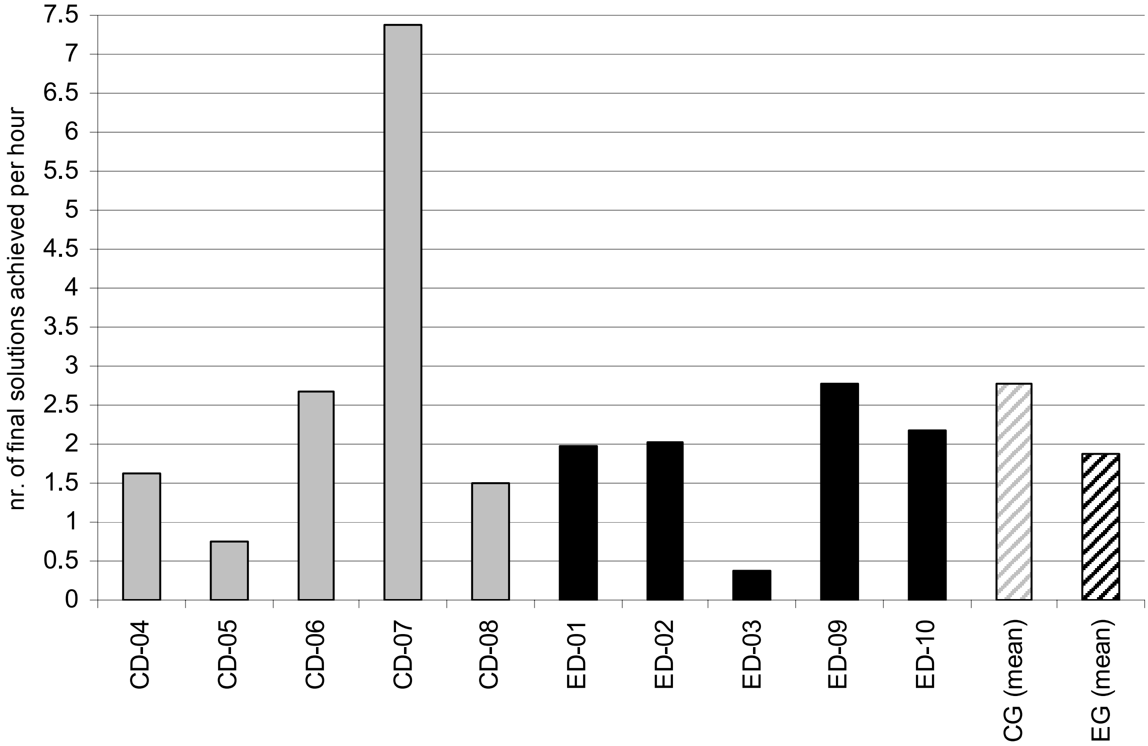


Figure 6-17: Number of final solutions achieved per hour

With 1.87 final solutions per hour the EG achieves less solutions per hour than the CG with 2.79 final solutions per hour.

Figure 6-18 shows the efficiency rates of CDs, EDs as well as the CG and the EG. The pattern in Figure 6-18 is nearly identical to the pattern in Figure 6-17 because the quality values achieved by the designers (Figure 6-13) are nearly identical, and thus the efficiency rates are mainly determined by the number of final solutions per hour.

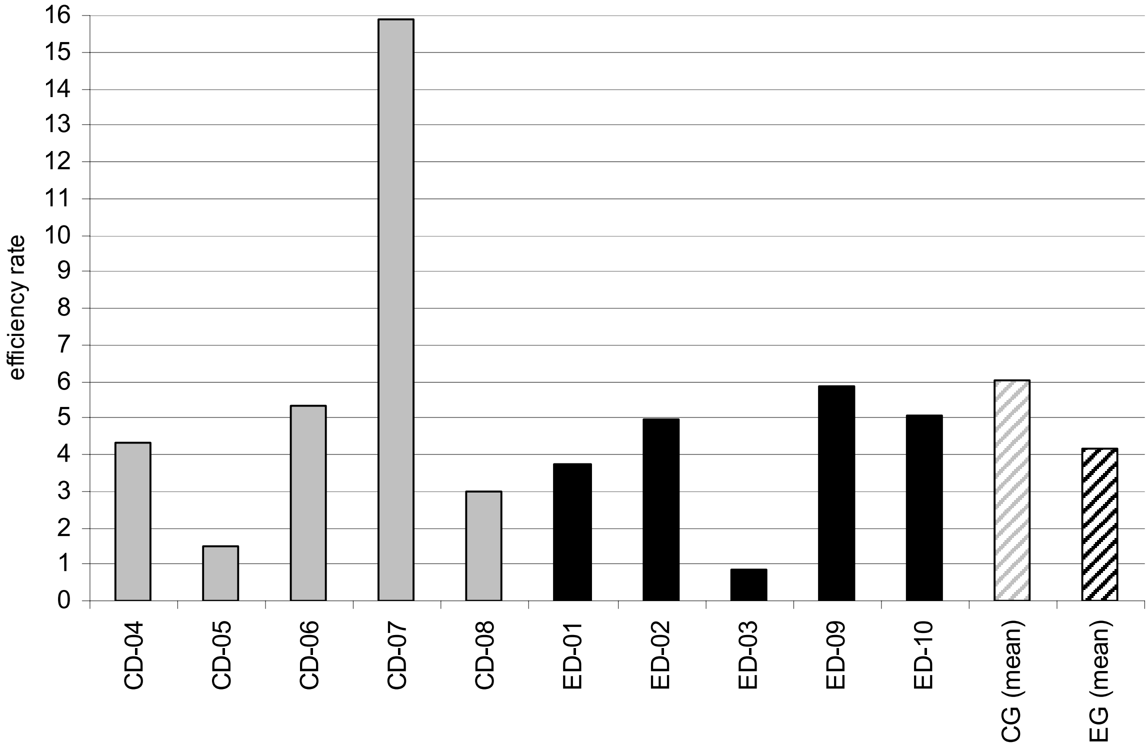


Figure 6-18: Efficiency rates

With an efficiency rate of 4.2 the EG is non-significantly less efficient than the CG with an efficiency rate of 6.03 (U test). This rejects hC-1.

Hypothesis hC-2

Compared to the group of designers working without SYCONDE, i.e. the CG, the group of designers working with SYCONDE, i.e. the EG, perceives to a higher level having worked efficiently.

Method mC-2

In Table 6-13, statements concerning the perceived efficiency of the design process, and the related ratings are given. For each statement, the designers were asked to tick the most appropriate rating after they had finished the design task.

Table 6-13: Statements and ratings concerning the perceived efficiency

Id.	Statements:	Ratings r:
a_{C-2}	I have the feeling of having worked efficiently.	not applicable at all: 0 rather not applicable: 1 neutral: 2 rather applicable: 3 fully applicable: 4
b_{C-2}	I have the feeling of having worked inefficiently.	
c_{C-2}	Also with more time I would not have had designed neither more nor better solutions.	
d_{C-2}	With more time I would have had designed more and/or better solutions.	

The efficiency perceived by each designer is represented through the median v_{C-2} of the numerical values of the ratings, i.e. $v_{C-2} = 0.25 * (r_{aC-2} + (4 - r_{bC-2}) + (r_{cC-2} + (4 - r_{dC-2}))$. The medians of the v_{C-2}-values of the corresponding designers, i.e. CDs and EDs, represent the efficiency perceived by the CG and the EG.

Results rC-2

Figure 6-19 shows the efficiency perceived by the CDs, EDs, the CG and the EG.

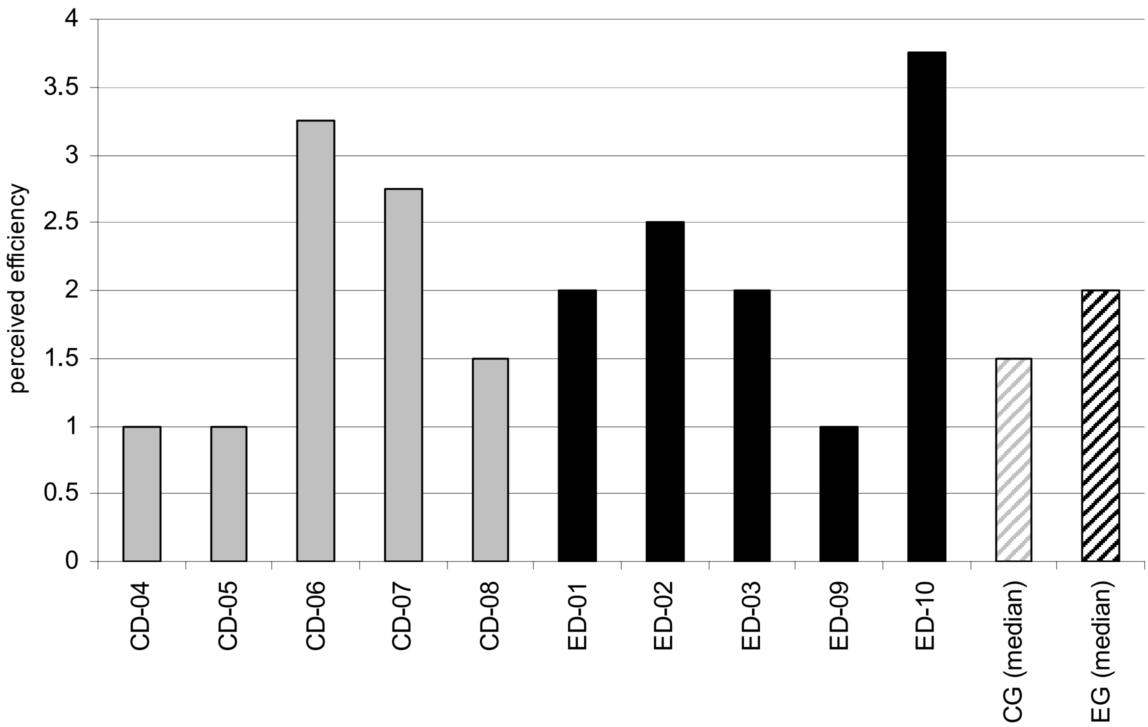


Figure 6-19: Perceived efficiency

With a value of 2, the EG perceives to a non-significantly higher level than the CG with a value of 1.5 that the design process was efficient (U test). For this reason, hypothesis hC-2 cannot be confirmed.

Hypothesis hC-3

The group of designers working with SYCONDE, i.e. the EG, perceives SYCONDE as a support for working efficiently.

Method mC-3

In Table 6-14 a statement concerning the perceived support through SYCONDE for working efficiently, and the related ratings are given. The EDs are asked to tick the most appropriate rating for this statement.

Table 6-14: Statement and ratings concerning the perceived support of SYCONDE

Id.	Statement:	Ratings r:	
$a_{C\text{-}3}$	SYCONDE supported me in working efficiently.	not applicable at all:	0
		rather not applicable:	1
		neutral:	2
		rather applicable:	3
		fully applicable:	4

The support each ED perceived through SYCONDE for working efficiently is represented by the numerical value of the rating, i.e. $a_{C\text{-}3}$. The median of the EDs represents the support perceived by the EG.

Results rC-3

The EG perceives to have had some support of SYCONDE for working efficiently. Figure 6-20 shows that three designers (ED-02, -03, -10) perceive some support while two designers (ED-01, -09) perceive rather no support. This neither confirms nor rejects hypothesis hC-3.

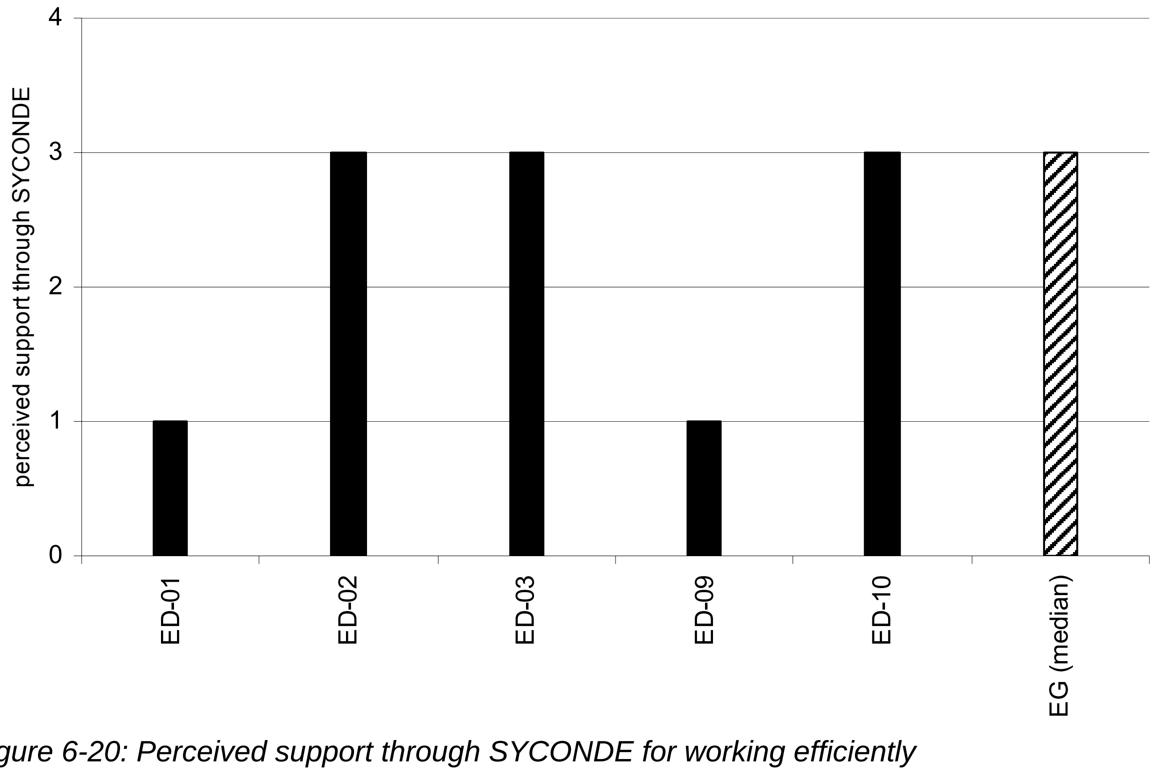


Figure 6-20: Perceived support through SYCONDE for working efficiently

Discussion

CD-07 achieved 7.39 final solutions per hour (Figure 6-17) while the remaining designers (EDs and CDs) achieved between 0.37 (ED-03) and 2.79 (ED-09). Due to this considerable difference it seems reasonable to rate CD-07 as an outlier. For the difference, no specific cause can be determined. CD-07 is one of the two CDs who stated that they have participated in about ten design projects.

If the number of final solutions achieved per hour as well as the efficiency rate are recalculated without CD-7, the CG achieved with a number of 1.64 less final solutions per hour (Figure 6-21) and with 3.54 a non-significantly lower efficiency rate than the EG (Figure 6-22) (U test).

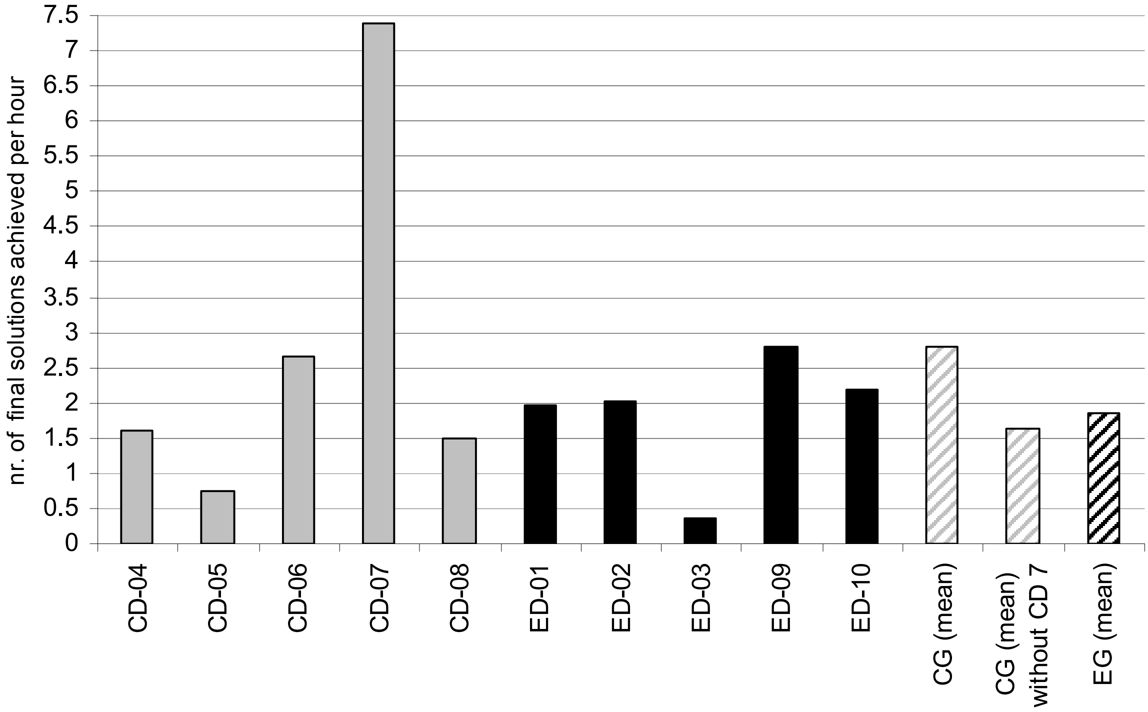


Figure 6-21: Number of final solutions achieved per hour with CD-07 rated as an outlier

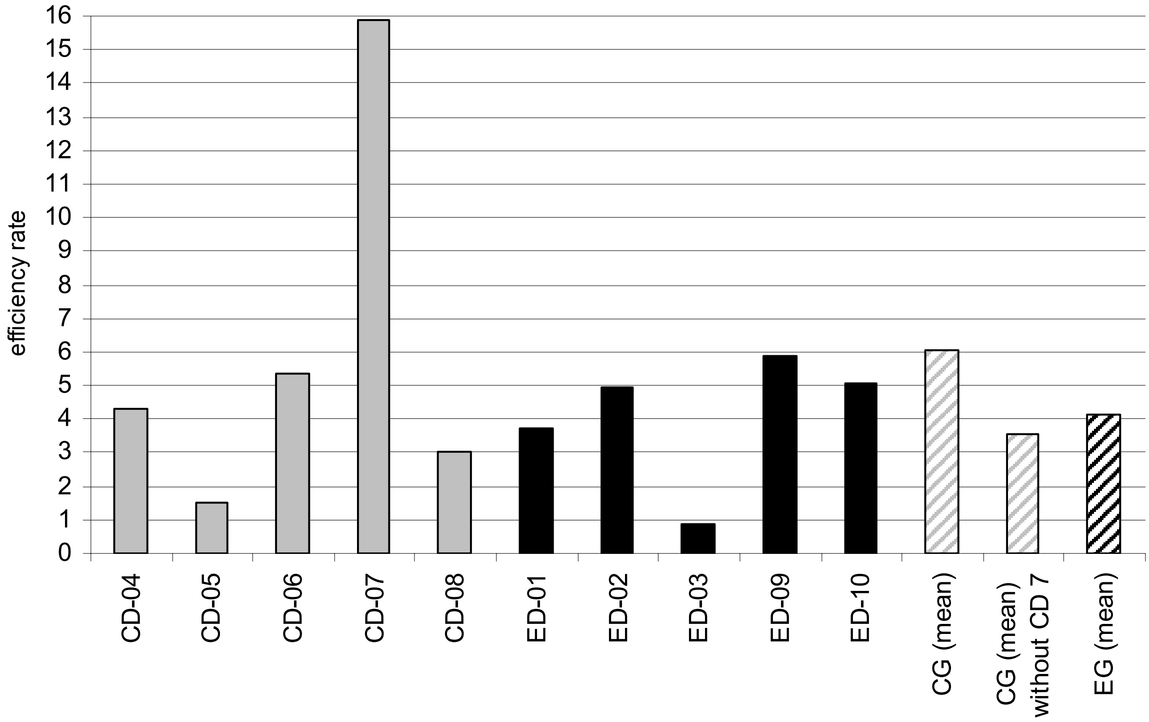


Figure 6-22: Efficiency rates with CD-07 rated as an outlier

The number of final solutions achieved per hour by the EG might be larger when the EDs are more familiar with SYCONDE. Further, SYCONDE is in English so that the designers might have needed extra time for completely understanding the steps.

Although the perceived efficiency and the achieved efficiency rates are correlating for the groups, these differ for the individual designers. This might be caused through the difficulty of assuming the efficiency which depends on three factors, the achieved number of final solutions, the achieved quality and the required working time.

6.5 Opinions concerning the design process and SYCONDE

This section focuses on the most negative and positive experiences of CDs and EDs during working on the design task (Section 6.5.1), on the disadvantages and advantages of SYCONDE from the EDs point of view (Section 6.5.2), on proposals of the EDs for improving SYCONDE (Section 6.5.3), and on their willingness to use SYCONDE again (Section 6.5.4).

6.5.1 Most negative and positive experiences

The most negative and positive experiences during working on the design task were identified through the following open-ended questions answered by the CDs and EDs after they had finished the design task.

- Which were the two most negative experiences during working on the design task?
- Which were the two most positive experiences during working on the design task?

CDs mentioned in total seven negative experiences occurred during working on the design task. Four of these seven were clustered and summarised to two negative experiences. These two negative experiences, the lack of ideas, derived from the statements of CD-07, and -08, and the lack of experience, derived from the statements of CD-05 and -06, are commonly allocated to the CDs.

EDs mentioned in total eight negative experiences occurred during working on the design task. Three of these eight were clustered and summarised to one negative experience. This negative experience, the complexity of step 4, i.e. selecting/generating joining concepts, derived from the statements of ED-01, -09 and -10, is commonly allocated to the EDs.

CDs mentioned in total eight positive experiences occurred during working on the design task. Three of these eight were clustered and summarised to one positive experience. This positive experience, having reached the target, i.e. having realised solutions which might satisfy the requirements, derived from the statements of CD-04, -06 and -08, is commonly allocated to the CDs.

EDs mentioned in total nine positive experiences occurred during working on the design task. Four of these nine were clustered and summarised to two positive experiences. These two positive experiences, the guidance through the design process derived from the statements of ED-01 and -10, and the possibility of generating novel connections, derived from the statements of ED-03 and -09, are commonly allocated to the EDs

6.5.2 Biggest disadvantages and advantages of SYCONDE

The biggest disadvantages and advantages of SYCONDE were identified through the following open-ended questions answered by the EDs after they had finished the design task.

- What do you think are the biggest disadvantages of SYCONDE?
- What do you think are the biggest advantages of SYCONDE?

EDs mentioned in total eight disadvantages of SYCONDE. Four of these eight disadvantages were clustered and summarised to one disadvantage. This disadvantage, the complexity of SYCONDE, derived from the statements of ED-01, -03, -09, and -10, is commonly allocated to the EDs.

EDs mentioned in total seven advantages of SYCONDE. All of these seven advantages were clustered and summarised to three advantages. These three advantages, the provision of a method, derived from the statements of ED-01, -02 and -10, the systematic, derived from the statements of ED-01 and -03, and the consideration of many solution variants, derived from the statements of ED-03 and -09, are commonly allocated to the EDs.

6.5.3 Proposals for improving SYCONDE

The proposals for improving SYCONDE were identified through the following open-ended questions answered by the EDs after they had finished the design task.

- What would you like to improve of SYCONDE?

Only two EDs made proposals, namely to provide further information for a quicker understanding and to accelerate the procedure.

6.5.4 Willingness to use SYCONDE again

The willingness to use SYCONDE again for further design tasks was identified through the ratings EDs gave for the statements listed in Table 6-15 after they had finished the design task and is represented through the median v_W, i.e. $v_W = 0.5 * (r_{W1} + (4 - r_{W2}))$. The median resulting from the v_W–values of the EDs represents the willingness of the EG to use SYCONDE again.

Table 6-15: Statements and ratings concerning the willingness to use SYCONDE again

Id.	**Statements:**	**Ratings r:**	
W_1	The next time when I will design a connection, I will use SYCONDE again.	not applicable at all:	0
		rather not applicable:	1
		neutral:	2
W_2	The next time when I will design a connection, I will not use SYCONDE again.	rather applicable:	3
		fully applicable:	4

The EG were to some extend willing to use SYCONDE again for further design tasks.

Figure 6-23 illustrates that three designers (ED-02, -03, -10) show some willingness while two designers (ED-01, -09) does not really intend to use SYCONDE again. As disadvantages of SYCONDE, ED-01 mentioned that too much time was required for working with SYCONDE, while ED-09 complained that the design process was too much structured.

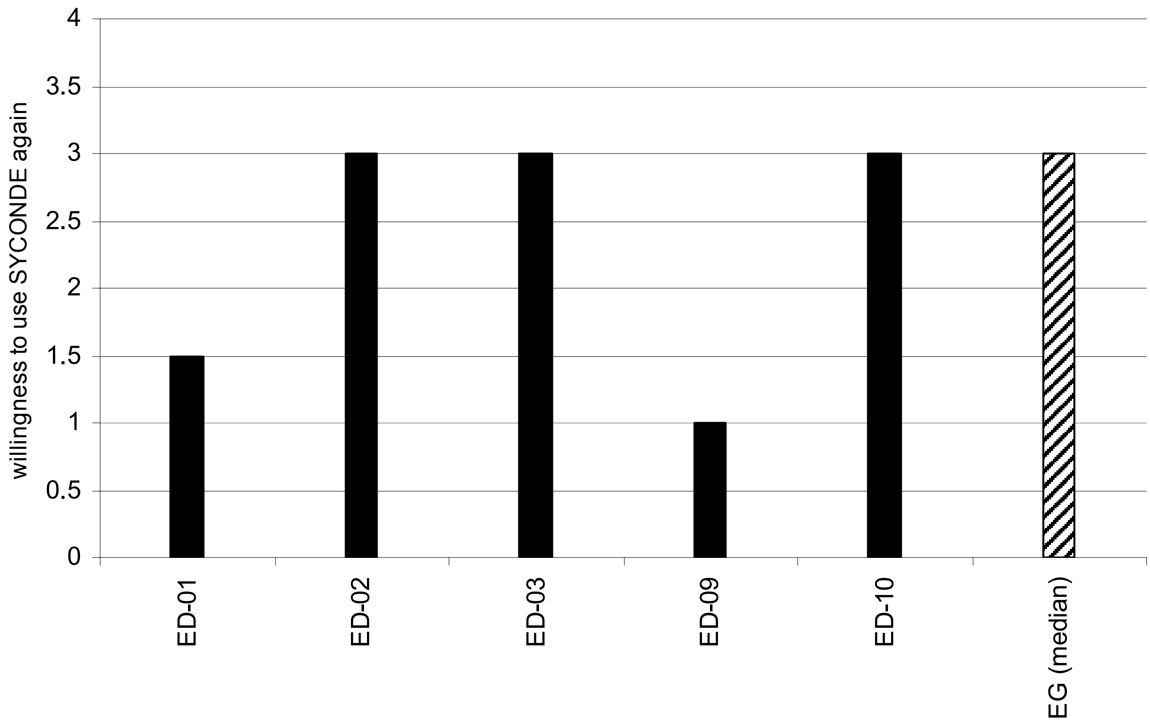


Figure 6-23: Willingness to use SYCONDE again

6.6 Conclusions

Even if most hypotheses could not be confirmed, a tendency towards the fulfilment of the SYCONDE functions of clearly structuring the solution path and considering a large solution space, as well as the SYCONDE aims, to support the designers and increase their effectiveness and efficiency, was observed. In the following this tendency is summarised.

The observations during the design processes showed that the experimental group structured the solution path non-significantly more clearly and considered a non-significantly larger solution space than the control group. The non-significantly lower effort experienced by the experimental group indicated only a slight support through SYCONDE. The experimental group achieved a non-significantly higher effectiveness than the control group and its efficiency was non-significantly higher after an outlier of the control group was ignored. Concerning the higher design times of the experimental group it is to be considered that the designers were not familiar with SYCONDE and that SYCONDE is in English, their second language. By means of the perceptions concerning the design process, the experimental group perceived to a non-significantly higher level than the control group that the solution path was structured, that the considered solution space was large and that the design process was efficient. By means of the perceptions concerning SYCONDE, the experimental group perceived SYCONDE as providing some support for structuring the solution path, considering a large solution space, designing connections, and working efficiently.

The negative experience of lacking ideas and experience mentioned by the control designers in the open-ended questions was not mentioned by the experimental designers. Only three of five experimental designers would use SYCONDE again, possibly because they perceived SYCONDE, specifically for step 4 as complex. In this step two dimensionally represented abstract solution variants are proposed to be transferred to the three-dimensional components to be assembled. The reduction of this complexity might improve the effectiveness and efficiency of designers using SYCONDE, and the willingness to use SYCONDE again.

7 Conclusions

The answers to the research questions, namely, how the solution space of connections can holistically be represented and whether SYCONDE supports designers, are summarised in Section 7.1. The reduction of complexity by implementing SYCONDE in a computer tool is the focus of Section 7.2.

7.1 Summary

In line with constantly changing product challenges, requirements for connections are also changing and, besides selecting existing connections, designers sometimes must generate novel ones. Concerning the support of the designers in these processes, existing approaches were investigated but none of these supported both the selection of existing and the generation of novel connections. Some of the approaches focused on the selection of existing connections. Their disadvantages are that the number of considered connections is restricted and that the databases in which these are stored must regularly be updated resulting in considerably maintenance effort. No approach was identified for generating novel connections. One approach showed in an abstract way the solution space of connections but did not describe the process of designing these. Only few approaches considered the interfaces of the components to be assembled. For supporting both the selection of existing and the generation of novel connections, the research question of how the solution space of connections can holistically be represented was answered. For this, those connections were considered that can also be applied to mass products, i.e. connections that realise a fixed arrangement under normal ambient conditions in all possible orientations and that do not require the supply of energy to hold this arrangement. Then, assembly and disassembly processes were split in subprocesses which can be identified for all kinds of connections, namely joining/separating and locking/unlocking. By means of these subprocesses, assembly and disassembly related properties of connections were identified and the connection characteristics determining these properties were defined. For describing the solution space of these characteristics, locking technologies and joining concepts were introduced. For indicating combinations of locking technologies and joining concepts, connection principles were established. All this was brought together in a novel connection classification scheme. Basing on this, a new approach for designing connections, SYCONDE, was developed. In SYCONDE, the focus is not on specific connections, but on the defined connection characteristics, their solution variants and their combination resulting in specific connections.

For the second research question whether SYCONDE supports the designer, the functions and aims of SYCONDE were formulated, evaluation questions were derived and hypotheses were formulated. Whether the hypotheses apply was evaluated in an experiment in which ten designers worked on a given task for designing connections. Five of the designers, the experimental designers forming the experimental group, worked with SYCONDE, while the other five designers, the control designers forming the control group, worked without SYCONDE. Even if most hypotheses could not be confirmed, a tendency was observed. The findings are listed in the following:

- Concerning a clear structure of the solution path it was found that the experimental group performed significantly more important activities and repeated two of these less frequently than the control group. Of these, the experimental group repeated one activity significantly less frequently than the control group.
- Concerning the considered solution space, the experimental group considered in four of five categories more solution variants than the control group. In the category 'locking technology' the experimental group considered significantly more solution variants than the control group.
- The effort experienced by the experimental group during working on the design task was lower, but not significantly, than that experienced by the control group.
- The final solutions of the experimental group had a non-significantly higher quality and suitability for the given task than those of the control group.
- The experimental group was non-significantly less efficient than the control group. After the elimination of an outlier of the control group, the efficiency of the experimental group was non-significantly higher than that of the control group.

Most experimental designers perceived SYCONDE as having supported them in their design process, but they stated also that its application required much time and that SYCONDE was complex, specifically step 4, i.e. selecting/generating joining concepts. It is assumed that this will be much easier for the designers, if they have more experience with SYCONDE. The work of Bender [Bender-04] argues that the application of a fresh, pure theoretically conveyed design methodology does not have a positive effect on the conceptual and early embodiment design phase or the quality of its solutions. Bender further states that it is not until the design methodology is trained over six months in a project that this quality increases [Bender-04, p. 233]. Relating this to SYCONDE, the support of the designers in designing connections and the quality of their final solutions might increase with further training. A possible way of reducing complexity is the implementation of SYCONDE in a computer tool.

7.2 Implementation of SYCONDE in a computer tool

The complexity for the designer resulting from the paper-based process description, the paper based provision of information, e.g. two dimensional sketches, and the paper-based documentation and management of the achieved solution variants can possibly be reduced through a computer tool. The general benefits, the benefits for step 4 which the designers perceived as complex, and the benefits for the subsequent steps also focusing on the geometrical connection characteristics, i.e. step 6 and 8, are described as scenarios in the following.

7.2.1 Scenario of the general benefits

After the designer confirms a step as finished, the tool leads over to the next step. This implies that:

- the results of the finished steps are transferred as input to those steps in which they should be processed further;
- a description of the actual step with its corresponding documentation form and leaflets with supportive information are provided;
- the requirements relevant for the actual step and labelled in step 2 as ‘demand’ or ‘wish’ are displayed.

In each step, the designer selects suitable solution variants from those stored in the tool or generates, assisted by the tool, novel solutions that are then stored for further design tasks. If sketches are necessary, the designer realises these supported by the tool. The tool further documents in *documentation forms* the solution variants resulting from each step and manages these. Thus, the designer is not confronted any more with paper work.

7.2.2 Scenario of the benefits for step 4, i.e. selecting/generating joining concepts

Instead of verbal descriptions and two-dimensional sketches, the tool provides three dimensional sketches and animated examples of *joining principles* and their application. Thus the designer easily understands these and their relation to the *interface types*. Supported by the tool, the designer makes three-dimensional sketches of the components to be assembled and selects suitable *interface types* through ticking boxes. The components with the selected interface types emerge on the screen where the designer can combine them to *joining concepts*. The designer selects those suitable with the given task as solution variants, and the tool enters these as three dimensional sketches in the *combination scheme*.

7.2.3 Scenario of the benefits for step 6, i.e. specifying connection concepts

For each *mechanically locked joining concept* the tool opens and identifies a separate *connection principles scheme*. In this the designer ticks for each *joining concept* suitable *connection principles*. If further *connection principles* are necessary, the designer sketches these assisted by the tool and the tool adds these to the *connection principles scheme* so that they are available for further design tasks. For the resulting connection concepts, i.e.

joining concepts and related *connection principles*, the tool creates identifiers composed of the identifier of the corresponding *joining concept* and *connection principle*.

7.2.4 Scenario of the benefits for step 8, i.e. selecting/generating locking methods

First, the tool allocates to each *connection concept* in accordance with its *locking technology* the corresponding *locking method list*. Then the *connection concepts* pop up on the screen, one after the other, with their corresponding *locking method lists*. For each *connection concept* the designer selects suitable *locking methods* through ticking boxes. If suitable locking methods are not available, the designer generates novel ones assisted by the tool and the tool adds these to the *locking method lists* so that they are available for further design tasks. The tool documents the resulting *final solutions* in the *final solution forms* and creates identifiers composed of the identifier of the corresponding *connection concept* and the used *locking method*.

7.3 Final statements

SYCONDE tends to have a positive influence on the design process. For strengthen this influence, the support designers perceive by using SYCONDE, must be increased. This can be realised through providing SYCONDE with further functions, e.g. a support for dimensioning the selected and generated connections, and through reducing the complexity of SYCONDE as already mentioned above.

SYCONDE should further be implemented in the design process of entire products. For this, the order in which connections are determined best in an entire product must be identified and the steps of SYCONDE must be synchronised with the steps of the product design process. For supporting designers in realising products satisfying different kinds of requirements concerning the connection design, e.g. realisation of a specific disassembly concept, use of similar connections, SYCONDE should analyse and manage all connections which are selected and generated for the product as well as their assembly and disassembly related properties and should provide suggestions for satisfying these requirements. For this, relevant requirements must be identified, rules for satisfying these requirements must be determined and algorithms for evaluating the suitability of particular connections must be defined.

Appendix A Terminology

In the following, the most important terms used in this thesis and their definitions are arranged in alphabetical order. Terms emerging in the definitions in *italics* are listed and defined separately in this list.

Additives:	All elements which are in addition to the *components* to be assembled necessary for realising a *connection*, e.g. solders, glues, bolts, nuts.
Adhesion:	Unity of *components* of different materials realised at their *interfaces*. Further split in *chemical adhesion*, *microstructural mechanical adhesion* and *macrostructural mechanical adhesion*.
Aligned trigger	Trigger which requires for its application specific kinematics and defined positions between tools and components.
Chemical adhesion:	Unity of *components* of different materials realised at their *interfaces* through intermolecular attraction.
Cohesion:	Unity of *components* of identical materials realised at their *interfaces* through intermolecular attraction.
Component:	Element with defined geometry and function.
Connection:	Technical solution restricting relative movement between two or more *components*, e.g. upper and lower housing part, and resulting in a fixed arrangement. This can be realised through the *components* to be assembled only, e.g. snap fit, or through combining these with *additives* like glue, bolts, nuts etc.
Connection concept:	Abstract level of a *connection*, describing the kind of locking/locking technology, the *components* to be assembled and the resulting *connection* geometry. Necessary *additives* are represented in an abstracted way.
Connection principle:	Abstract level of a mechanical *connection*, describing the *components* to be assembled in an abstracted way, the joining concept and the resulting *connection* geometry. Necessary fasteners are represented in an abstracted way.
Contact-based disassembly process:	Disassembly process requiring contact with the *connection* or the connected *components* because disassembly is initiated through movements and forces, e.g. rotation of bolt and nut relatively to each other, movement of the hook of a snap fit *connection*.
Contactless disassembly process:	Disassembly process not requiring contact with the *connection* or the connected *components* because disassembly is not initiated through movement and force but through triggers not requiring any alignment with the *connection* or the connected *components*. These triggers are further split in accordance with their transmissibility in *pathway* and *non-pathway triggers*.
Effect carrier:	Transmitter of a physical effect.
Fastener:	*Additive* with defined geometry and function (*components*) which realises the *connection* without changing its state of aggregation as this is the case for *additives* like solders and glues.
Final solutions:	Results of an entire design process.
Force field locking:	*Kind of locking,* where movements between *components* are restricted through a force field, e.g. magnetic field, vacuum.

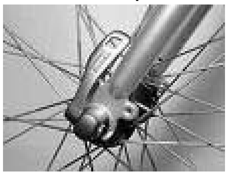
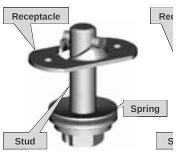
Interface:	Area where the *components* to be assembled are in contact with each other for realising a connection.
Joining concept:	Abstract representation of the *components* to be assembled with their *interface* geometry in joined condition.
Kind of locking:	Cluster of working principles restricting movements between *components*.
Locking method:	Explicit description of the locking process.
Locking technology:	General description of the locking process.
Macrostructural mechanical adhesion:	Unity of *components* of different materials realised at their *interfaces* through macrogeometrically meshing.
Material locking:	Kind of locking where movements between *components* are restricted through different material interactions.
Material recycling:	Reuse of material of products or *components* of these.
Mech I:	Mechanical *locking technology* restricting movements through *macrostructural mechanical adhesion*, i.e. geometrical interlocking of the *component interfaces*.
Mech II:	Mechanical *locking technology* restricting movements through mechanically transmitted forces and the resulting static friction.
Mech III:	Mechanical *locking technology* restricting movements through both *macrostructural mechanical adhesion*, i.e. geometrical interlocking, and mechanically transmitted forces as well as the resulting static friction.
Mechanical locking:	Kind of locking where movements between *components* are restricted through geometrical interlocking and/or mechanically transmitted forces.
Microstructural mechanical adhesion:	Unity of *components* of different materials realised at their *interfaces* through microgeometrically meshing.
Non-pathway trigger:	Trigger transmitted in atmosphere not requiring any specific pathway, e.g. alternating magnetic field.
Pathway trigger:	Trigger that must be transmitted through a specific pathway, e.g. electric current to be supplied through an electric conductor.
Product recycling:	Reuse of products or *components* of these under maintenance of their intended function.
Solution variants:	Intermediate results of the activities or steps in a design process.
To assemble:	To combine at least two *components* and restrict relative movements between these such that a fixed arrangement results. This process is split in the subprocesses joining, i.e. *to join*, and locking, i.e. *to lock*.
To disassemble:	To take *components* apart. This process is split in the subprocesses unlocking, i.e. *to unlock*, and separating, i.e. *to separate*.
To fasten:	To add and position *fasteners*. This process is part of the locking process, i.e. *to lock*.
To join:	To combine two or more single *components* such that the locking process can be performed. This process is a subprocess of assembling, i.e. *to assemble*.
To lock:	To maintain even under loading the joined state of the *components*. This may require *additives*. This process is a subprocess of assembling, i.e. *to assemble*.
To separate:	To move the *components* apart from each other. This process is a subprocess of disassembling, i.e. *to disassemble*.
To unfasten:	To remove *fasteners*. This process is allocated to unlocking, i.e. *to unlock*.
To unlock:	To enable separation of the *components*. This process is a subprocess of disassembling, i.e. *to disassemble*.

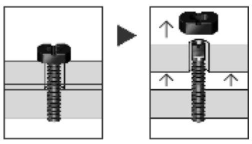
To unlock "at the push of a button":	Indicates the property of *connection*s that they can be disassembled through *unaligned triggers*, i.e. without being contacted, and the resulting possibility of unlocking these at the push of a button.
Unaligned trigger	Trigger which for its application neither requires specific kinematics nor defined positions between tools and components.

Appendix B Non- and partially destructive connections

The following table lists different connections supporting the non- and partially-destructive disassembly. Some of these connections are well known and daily used, other ones are novel. For the novel connections references to further literature are given.

Connection	**Assembly process**	**Disassembly process**
Suction cup		
Conventional suction cup	Moving the components together and push air out of the cavity.	Deforming the suction cup membrane
	Moving the components together in a vacuum chamber.	Moving the product into a vacuum chamber
	Moving the components together and push air out of the cavity.	Opening a valve situated between the area with vacuum and ambient pressure.
Suction gripper	Providing the cavity with vacuum	Providing the cavity with pressure
Magnetic connection		
Connection where each interface consists of both north and south pole. [Bruchhold-99]	Moving the components together. This is supported by the magnetic field.	Rotating the components relatively to each other around the axis parallel to the lines of magnetic flux and running through the parting line between the magnetic poles such that identical poles are overlaying and repelling each other.
Adhesive		
Adhesive with super paramagnetic particles [Pridöhl et al.-05, p. 78; Fraunhofer-06]	Identical to common adhesive connection	Activating an alternating magnetic field results in local heat. This solubilise the adhesive layer without changing the temperature of the components. For reassembly, new additives are necessary.

Connection	Assembly process	Disassembly process
Bonding		
LaNiAl-bonding of two components from aluminium [Suga et al. -93; Suga & Hosoda-00].	Cleaning and activating the component surfaces through ion bombarding or plasma irradiating and contacting these in clean atmosphere, e.g. vacuum, inert gases.	Providing a hydrogen atmosphere pulverises LaNiAl and results in disengagement of the bonding. For reassembly new additives are necessary.
Bolt-nut connection, continuation on next page		
Quick clamper for bike wheels 	Turning the lever around 90° to 180° in counter clockwise direction. Preload can be adjusted.	Turning the lever around 90° to 180° in clockwise direction.
Bolt nut connection with a thread from shape memory alloy [Chiodo et al.-97, -99a, -99b, -02, Chiodo & Boks-99; Jones et al.-02, Jones et al.-04]	Identical to common bolt-nut connection. Preload can be adjusted.	• Identical to common bolt-nut connection. • Changing the temperature results in disengagement of the threads.
Nut from cardboard consisting of Methyl Cellulose or Carboxyl Methyl Starch [Neubert-00, (pp. 104].	Identical to common bolt-nut connection. Preload can be adjusted.	• Identical to common bolt-nut connection. • Providing water with defined pH-value and temperature results in solubilisation of the nut. For reassembly new additives are necessary.
Quarter turn fastener 	Rotating around 90° in clockwise direction Preload cannot be adjusted.	Rotating around 90° in counter clockwise direction.
Fast Nut of Giehl Systems  [Schnellemutter-07]	• Identical to common bolt-nut connection. • Pushing opened fast nut on the bolt shaft. Preload can be adjusted.	• Identical to common bolt-nut connection. • Pulling at the nut.

Connection	**Assembly process**	**Disassembly process**
Bolt-nut connection ,continuation		
“TwinNut” of TwinNut GmbH  [Zimmermann-07; Twinnut-07]	Assembling the nut on the bolt. Preload can be adjusted.	Shortly rotating for reducing the preload force and then taking the nut halves radially apart from the bolt.
Removable bolt head type **I**, developed for the Collaborative Research Centre (CRC) 281  [Klett et al.-03b]	Identical to common bolt-nut connection. Preload can be adjusted.	• Identical to common bolt-nut connection. • Pulling at the bolt head.
Removable bolt head type **II**, developed for the Collaborative Research Centre (CRC) 281  [Klett et al.-03a]	Identical to common bolt-nut connection. Preload can be adjusted.	• Identical to common bolt-nut connection. • Providing an electric current resulting in melting of the melting element and disassembly of the bolt head. For reassembly new additives are necessary.
Screw head from shape memory alloy  [Sakai et al.-03; Sharp-04].	Identical to common bolt-nut connection. Preload can be adjusted.	• Identical to common bolt-nut connection. • Changing the temperature results in disengagement of the screw head.
Cantilever snap fit, continuation on next page		
Gardena system for connecting flexible pipes with water tabs  [Gardena-06]	Pushing the snap fit together	Pulling at the red ring deforms the hook and results in disengagement of the snap fit.
Hook with piezo element [Braunschweig-04]		Providing a voltage to the Piezo-element deforms the hook and results in disengagement of the snap fit.

Connection	Assembly process	Disassembly process
Cantilever snap fit, continuation		
Hook linked with pressure sensor [Braunschweig-04]	Pushing the snap fit together	Increasing a pressure at the pressure sensor deforms the hook and results in disengagement of the snap fit.
Hook with magnetic anchor [Braunschweig-03]		Activating a magnetic field deforms the hook and results in disengagement of the snap fit.
Hook linked with muscle wire from shape memory alloy [Jones et al.-04]		Changing the temperature at the muscle wire deforms the hook and results in disengagement of the snap fit.
Hook from shape memory alloy [Chiodo et al.-97, -99a, -99b, -02, Chiodo & Boks-99; Jones et al.-02, Jones et al.-04] [Tanskanen & Takala-03]. [Sakai et al.-03; Sharp-04]		Changing the temperature deforms the hook and results in disengagement of the snap fit.
Multiple hooks linked with a central lever [Braunschweig-04]		Moving the central lever deforms all hooks and results in disengagement of all snap fits.
Snappers are linked with a retainer with water, i.e. “freezing element” [Neubert-00, (pp. 110].		Providing freezing-temperatures elongates the water. This deforms the hook and results in disengagement of the snap fit.
Multiple hooks and a defined common, temperature-sensible point through which all hooks can be deformed [Nishiwaki et al.-00; Li et al.-01],		Providing heat to the centralised point elongates the components. This deforms the hooks and results in disengagement of the snap fits.
More than one hook linked with a pressure sensor [Neubert-00, pp. 84; Willems et al.-06]		Increasing the ambient pressure at the pressure sensor deforms the hook and results in disengagement of the snap fit.
Hose clip		
Hose clip with melting element, developed for the Collaborative Research Centre (CRC) 281  [Klett et al.-03a]	Identical to conventional hose clip with screw.	• Identical to conventional hose clip with screw. • Providing an electric current melts the melting element and results in disengagement of the hose clip. For reassembly new additives are necessary.

Connection	Assembly process	Disassembly process
Velcro structure		
Textile velcro structure	Pressing the components together	Peeling the components apart from each other.
Application of the velcro structure to metallic materials [Schmidt-04]		
Realisation of the velcro structure in nanostructure dimensions [Dewald-03].		

Appendix C SYCONDE

In Appendix C.1, the process of designing connections with SYCONDE is described. For this, the particular steps are explained by the workbook and, as an example for the documentation of the emerging results, documentation forms are added which were filled in by an experimental designer working on the design task described in Appendix D.1. The workbook refers at some places to the supportive information. This can be found in Appendix C.2.

C.1 Workbook and documentation forms

Each step is structured through the following elements:

- Description: describes the purpose and aim of a step;
- Documentation form: refers to the form for documenting the solution variants of a step;
- Supportive information: refers to the leaflets with useful information for solving the step;
- To Do: lists the actions to be undertaken for solving the step.

Only those elements are mentioned which are necessary for a particular step.

Step 1: Preparation

Analysing if a connection is necessary

Documentation form:

- Question scheme (Figure C-1)

To Do:

- Answer the questions in the question's scheme by ticking the boxes.
- Continue with SYCONDE if at least one of the questions in the scheme is answered positively.
- Abandon SYCONDE if all questions are answered negatively and consider the realisation of both components as one unit.

Step 1: Question scheme

Questions scheme:	Yes (positive)	No (negative)
During operation of the product, the components move relatively to each other? Only gross motion should be considered – small motions that can be accommodated by elastic hinges, for example, are not sufficient for a positive answer. [Boothroyd and Dewhurst - 1987]		X
Must the components be of different materials than or be isolated from each other? Only fundamental reasons concerned with material properties are acceptable. [Boothroyd and Dewhurst - 1987]	X	
Must the components be separated from each other because otherwise necessary assembly or disassembly of other separate components would be impossible? [Boothroyd and Dewhurst - 1987]		X
Are there other important reasons for separating the components (e.g. one component is produced at location A, the other at location B)?	X	
Is at least one of the components used in different assemblies and hence need to be available separately?	X	

Figure C-1: Question scheme

Specifying the characteristics and properties of the components to be connected

Documentation form:
- Component scheme (Figure C-2)

To Do:
- Enter the names and the materials of the components to be connected. If their materials are not specified they can be determined without restriction.

Step 1: Component scheme

Component 1
Name: Laugenbehälter
Material: PP GF 30

Component 2
Name: Frontgewicht
Material: Beton

Figure C-2: Component scheme

Step 2: Specifying connection requirements

Description:

Requirements labelled with "D" (Demand) are relevant for the determination of solution variants in the following steps. Solution variants not fulfilling these requirements are to be rejected. Requirements labelled with "W" (Wish) are not relevant for the determination of solution variants but are used for the formulation of evaluation criteria. Requirements not labelled, are not relevant for the considered design task and should not be considered further.

Documentation form:
- Requirements list (Figure C-3)

To Do:
- Select from the requirements list those requirements to be fulfilled and tick "D" (Demand) or "W" (Wish). Demands (D) must be satisfied. The satisfaction of wishes (W) is not obligatory but would be advantageous.
- Enter values for Req. 2.5.
- Add additional requirements as and if necessary.

Step 2: Requirements list

Nr.	Connection requirements	D	W
1.	**Requirements concerning the components**		
1.1	The material of component 1 should not be changed.	X	
1.2	The material of component 2 should not be changed.	X	
1.3	A shape change of component 1 is not possible or only under constrictions.	X	
1.4	A shape change of component 2 is not possible or only under constrictions.	X	
2.	**Requirements concerning the connection function**		
2.1	More than 2 components should be connected.		
2.2	To prevent movements and vibrations, respectively, the connection should be free of clearance.	X	
2.3	The connection should stand dynamical stress.	X	
2.4	The function of the connection should be independent from permanent energy supply.	X	
2.5	The connection should work between the following temperatures: 10 - 106°C	X	
2.6	The unintended unlocking and separating of the components results in danger of live or health etc. but at least has a high seriousness. Hence, higher safety standards against unlocking and separating of the components should be achieved.	X	
3.	**Requirements concerning the connecting and disconnecting processes**		
3.1	Locking should be achieved through movement and/or deformation.		
3.2	Unlocking should be achieved through movement and/or deformation.		
3.3	Additives (additional materials, separate fasteners) should not be necessary.	X	
3.4	Geometry or molecular structure of the components should not change through locking and unlocking. (Prerequisite for a connection which can be connected and disconnected frequently!)	X	
3.5	Additives (materials/fasteners) should stand frequent locking and unlocking cycles.	X	
3.6	Joining and/or separating should be possible in many directions.		X
3.7	Joining and/or separating should be realised on little space.		X
3.8	The connecting steps should be performed through similar/same triggers.		
3.9	The disconnecting steps should be performed through similar/same triggers.		
3.10	Locking should be performed manually without tool.		X
3.11	Unlocking should be performed manually without tool.		X
3.12	Locking should be realised through unaligned triggers (without the necessity of performing specific kinematics or providing defined positions between tools and components / prerequisite for simultaneous locking "at the push of a button").		
3.13	Unlocking should be realised through unaligned triggers (without the necessity of performing specific kinematics or providing defined positions between tools and components / prerequisite for simultaneous unlocking "at the push of a button").		
4.	**Additional connection functions**		
4.1	Overload protection should be provided, i.e. in case of overload the connection becomes disconnected in order to prevent damage of the components.		X

Figure C-3: Requirements list

Step 3: Rejecting unfeasible locking technologies

Documentation form:

- Combination scheme (Figure C-9)

Supportive information:

- Locking technology list (Appendix C.2.1)

To Do:

- Open a combination scheme and cancel, supported by the locking technology list, the locking technologies not fulfilling those requirements of step 2 listed below and having been labelled with “D”.

Requirements:

Components

- *Req. 1.1/1.2: The material of component 1 and/or component 2 should not be changed.* (Labelled D in the example.)

Cancel the locking technologies which are not suitable for the materials of the considered components.

Connection function

- *Req. 2.1: More than 2 components should be connected.*

Cancel the locking technologies which are not able to lock the number of components to be connected.

- *Req. 2.3: The connection should withstand dynamical stress.* (Labelled D in the example.)

Cancel the locking technologies which cannot be stressed dynamically.

Assembly and disassembly processes

- *Req. 3.1: Locking should be achieved through movement and/or deformation.*

Cancel the locking technologies which cannot be achieved through movement and/or deformation.

- *Req. 3.3: Additives, i.e. materials or fasteners, should not be used.* (Labelled D in the example.)

Cancel all locking technologies which require additives for locking.

- *Req. 3.4: Geometry or molecular structure of the components should not change through locking and unlocking. This is a prerequisite for a connection that frequently can be assembled and disassembled.* (Labelled D in the example.)

Cancel the locking technologies changing through locking or unlocking the geometry or the molecular structure of the components.

- *Req. 3.5: Additives, i.e. materials or fasteners, should withstand frequent locking and unlocking cycles.* (Labelled D in the example.)

Cancel the locking technologies with additives which are not able to withstand frequent locking and unlocking cycles.

Step 4: Selecting/generating joining concepts

Description:

In accordance with the orientation of their normal vectors, component interfaces are geometrically classified in *planar* and *profiled*. Planar interfaces have parallel normal vectors; profiled interfaces have diverging or intersecting normal vectors. The profiled ones are further classified in *convex*, i.e. interfaces with diverging normal vectors, and *concave*, i.e. interfaces with intersecting normal vectors. This results in the interface types illustrated in Figure C-4.

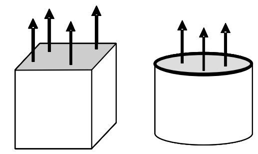
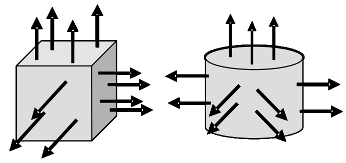
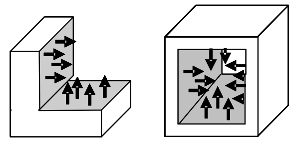
Interface type	**Planar,** i.e. parallel normal vectors		**Convex,** i.e. diverging normal vectors		**Concave,** i.e. intersecting normal vectors	
Sketch Faces representing the interface are grey.	 Cuboid: single face	Cylinder: single basic face	 Cuboid: from two up to all faces.	Cylinder: -lateral face; -more than two faces.	 Faces of a notch	Faces of a hole

Figure C-4: Interface types

If these interface types are combined with each other, two useful combinations namely planar/planar and convex/concave emerge. Components joined through planar interfaces are defined as a *planar joining concept*, abbreviated by *p*; those joined through convex and concave interfaces are defined as *convex/concave joining concept*, abbreviated by *cc*. Planar joining concepts only restrict one relative movement while convex/concave ones restrict between two and five. This results in different degrees of freedoms and implies that components of planar joining concepts can be joined and separated in five directions while those of convex/concave joining concepts can be joined and separated from one to four directions (Figure C-5).

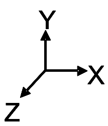
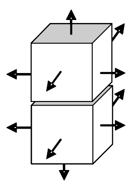
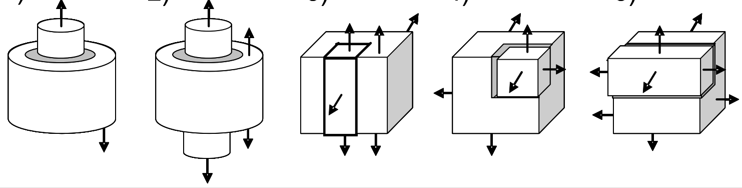
	Examples of joining concepts:					
	planar (p)	convex/concave (cc)				
 		1)	2)	3)	4)	5)
						
Degree of freedom:	5	1	2	3	3	4

Figure C-5: Degrees of freedom of different joining concepts

If a concave interface consists of faces aligned relatively to each other under an angle α larger than 270°, the faces are defined as being situated opposite each other. In Figure C-6 this is illustrated by examples of concave interfaces with opposite and not opposite situated faces.

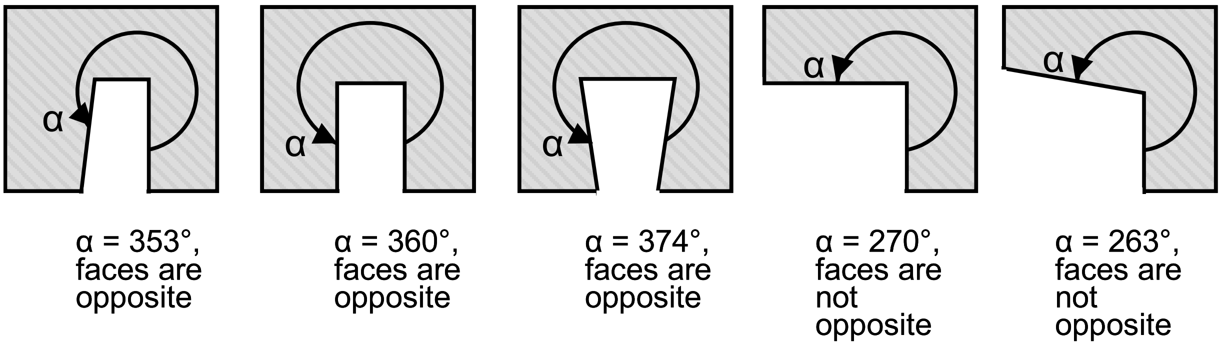


Figure C-6: Examples of concave interfaces with opposite and not opposite situated faces

A component with concave interface and opposite situated faces can entangle a component with a corresponding convex interface (see convex/concave joining concepts no. 1 – 3 in Figure C-5). In this case, locking through static friction can be realised through mechanically transmitting a force between the opposite situated interface areas. This is the basis for connections like press fits and those realised through hose clamps or wedges (Figure C-7).

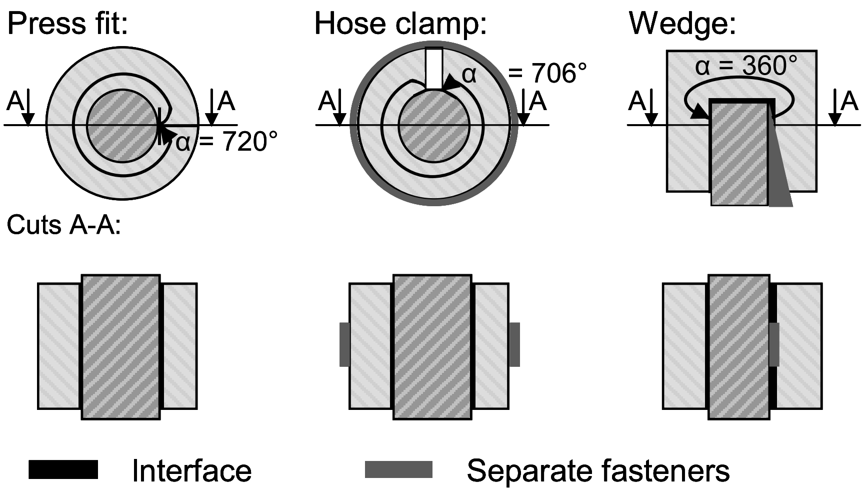


Figure C-7: Cross sections of connections locked through concave interfaces with opposite situated faces

In accordance with their different interface characteristics and locking properties, convex/concave joining concepts are classified (Figure C-8) into:

- *type A*-joining concepts without opposite situated interface areas, abbreviated through *ccA* (see convex/concave joining concepts no. 4 and 5 in Figure C-5);
- *type B*–joining concepts with opposite situated interface areas, abbreviated through *ccB* (see convex/concave joining concepts no. 1 - 3 in Figure C-5).

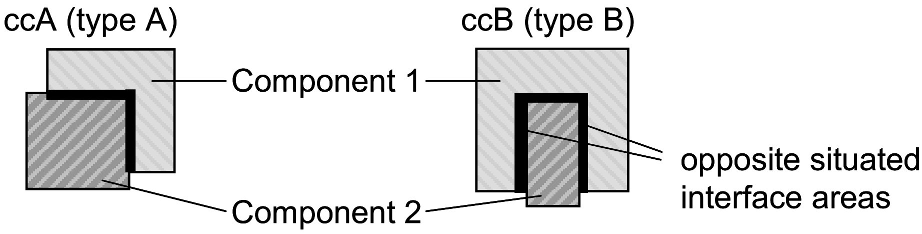


Figure C-8: Examples of ccA - and ccB - joining concepts

Through varying the component interface types, different joining concepts can be realised.

Documentation form:
- Combination scheme (Figure C-9)

To Do:
- Select/generate for the components to be connected suitable joining concepts fulfilling those requirements of step 2 listed below and having been labelled with “D”.
- Enter for each of the resulting joining concepts a sketch in the combination scheme and describe its type through one of the following options:

  o planar (p);
  o convex/concave Type A (ccA);
  o convex/concave Type B (ccB).

Requirements:

<u>Components</u>

- *Req. 1.3/1.4: A shape change of component 1 and/or component 2 is not possible or only under restrictions.* (Labelled D in the example.)

Derive joining concepts which can be realised without shape changes or with those corresponding to the requirements.

<u>Requirements connection function</u>

- *Req. 2.6: The unintended unlocking and separating of the components has highly negative effects, e.g. danger for live or health. Hence, higher safety standards against unlocking and separating of the components should be achieved.* (Labelled D in the example.)

To achieve higher safety standards, the joining concept should absorb loads in more than one direction. While the planar joining concept absorbs loads only in one direction, the convex/concave joining concepts can absorb loads in two up to five directions. With convex/concave joining concepts separating is less probable because less movements are possible than with planar joining concepts.

<u>Assembly and disassembly processes</u>

- *Req. 3.3: Additives, i.e. materials or fasteners, should not be used.* (Labelled D in the example.)

Here, only relevant for mechanical locking technologies:

Determine convex/concave joining concepts of Type B (ccB) or integrate/attach separate fasteners later (step 8) into/to the components.

- *Req. 3.6: Joining and/or separating should be possible in many directions.* (Labelled W in the example.)

Planar joining concepts can be joined and separated in five different directions of the general 3D-orthogonal system. Depending on the specific interface geometry, convex/concave joining concepts can be joined and separated in one up to four different directions (Figure C-5).

- *Req. 3.7: Joining and/or separating should be realised on little space.* (Labelled W in the example.)

Under restricted space, joining and separating is more likely with planar interfaces where the components can be moved in five directions, than with convex/concave interfaces where the components can be moved only in one up to four directions (Figure C-5).

Step 5: Combining locking technologies and joining concepts

Documentation form:

- Combination scheme (Figure C-9)

To Do:

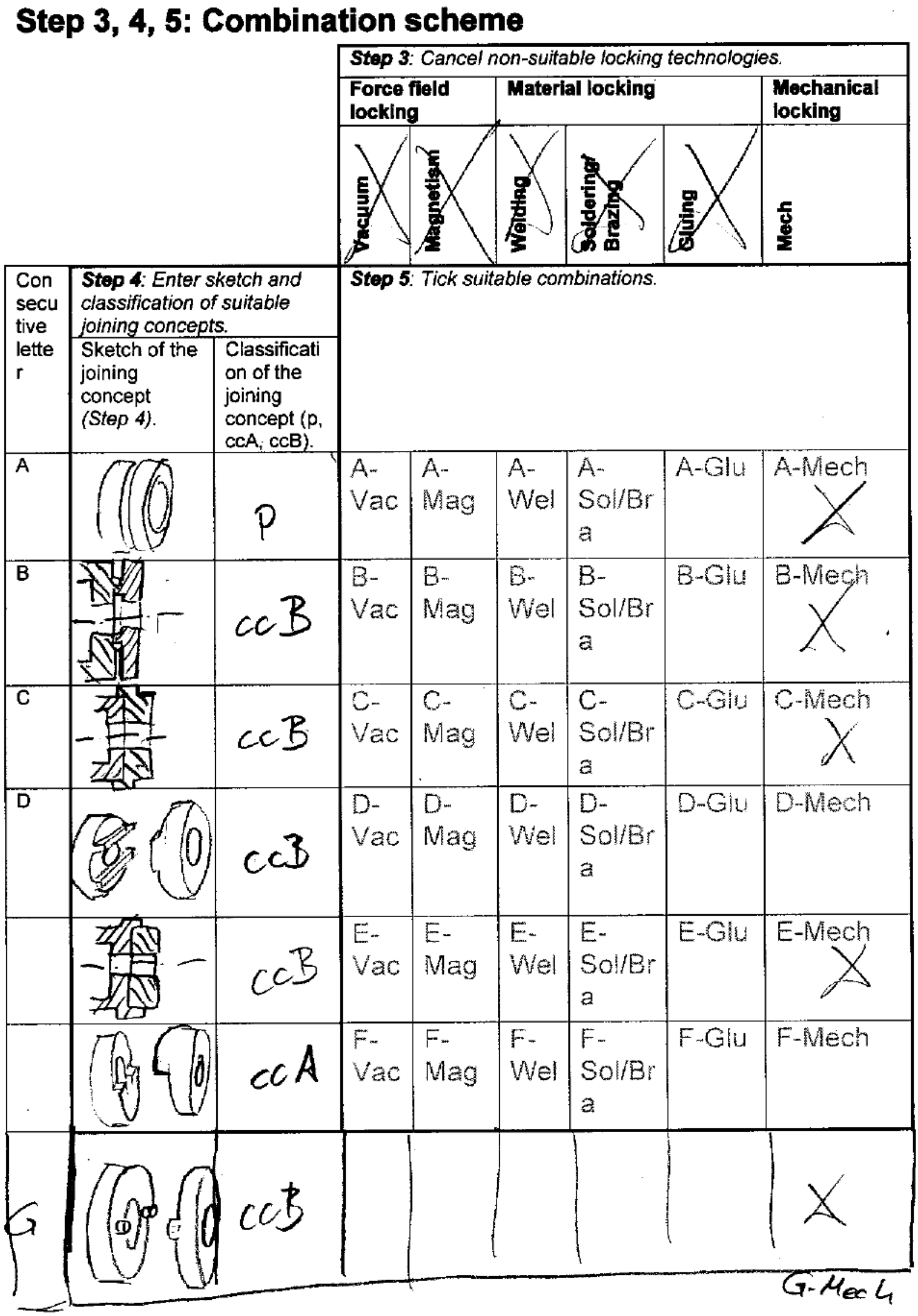
- Determine suitable combinations of the locking technologies accepted in step 3 and the joining concepts selected/generated in step 4 fulfilling those requirements of step 2 listed below and having been labelled with “D”.
- Mark the suitable combinations through ticking the corresponding cells.

Requirements:

<u>Connection function</u>

- *Req. 2.6: The unintended unlocking and separating of the components has highly negative effects, e.g. danger for live or health. Hence, higher safety standards against unlocking and separating of the components should be achieved.* (Labelled D in the example.)

To achieve higher safety standards, the joining concept should absorb loads in more than one direction. While the planar joining concept absorbs loads in only one direction, the convex/concave joining concept can absorb loads in two up to five directions. With convex/concave joining concepts separating is less probable because less movements are possible than with planar joining concepts.



Crosses in the first line indicate locking technologies cancelled in step 3.
Crosses in the matrix indicate combinations of locking technologies and joining concepts determined in step 5.

Figure C-9: Combination scheme

Step 6: Specifying connection concepts

This process step is described individually for each kind of locking.

Force field and materially locked joining concepts

Description:

The force field and material kinds of locking are initiated directly at the component interfaces and thus the geometrical characteristics of the connection are already determined through the joining concept. Connection concept and joining concept are identical and have the same **identifier in the following.**

To Do:

- Nothing is to be done in this step.

Mechanically locked joining concepts

Description:

The mechanical kind of locking can be realised through the interfaces of the components to be assembled only, or through additional components, i.e. fasteners. Fasteners initiate locking from outside the component interfaces and can be placed at different locations, e.g. they can entangle or pierce the components. This results in a large number of connection principles. Connection concepts are realised through allocating suitable connection principles to the considered joining concepts. The connection principles are listed in the connection principle scheme. Two types of connection principles, namely the *standard* and the *special* one are distinguished. While the standard ones can be realised with all joining concepts, the special ones can only be realised with convex/concave Type B (ccB) joining concepts.

Documentation form:

- Connection principles scheme (Figure C-10)

To Do:

- Open for each joining concept a connection principles scheme and enter its identifier determined in the combination scheme.
- Tick in each connection principles scheme those connection principles suitable for the considered joining concept and fulfilling those requirements of step 2 listed below and having been labelled with “D”.
- Consider the modification of existing or the generation of novel connection principles, if there are no suitable ones in the connection principles scheme, and add these to the scheme.

Requirements:

Components

- *Req. 1.3/1.4: A shape change of component 1 and/or component 2 is not possible or only under restrictions.* (Labelled D in the example.)

The application of the listed connection principles can require different shape changes of the components. The necessary shape changes are mentioned for each connection principle in the connection principles schemes. Select only connection principles without shape changes or those corresponding to the requirements.

Connection function

- *Req. 2.1: More than 2 components should be connected.*

With some connection principles more than two components can be connected. This is identified in the connection principles scheme. Select the connection principles according to the number of components to be connected.

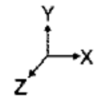
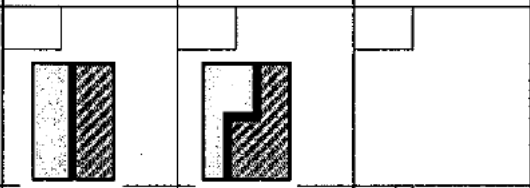
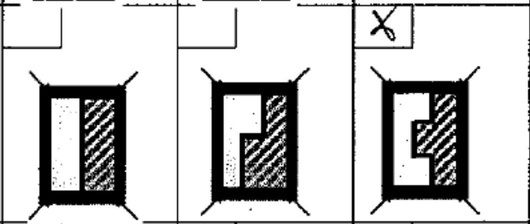
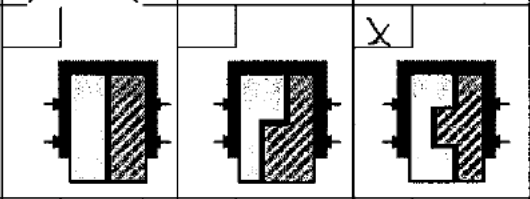
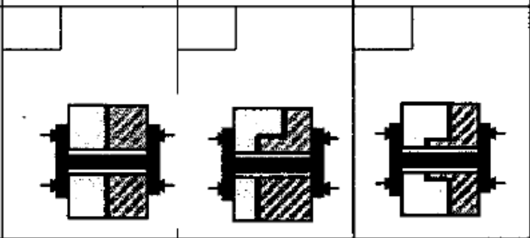
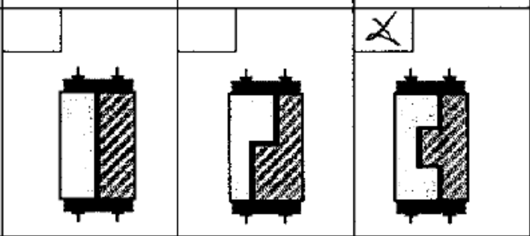
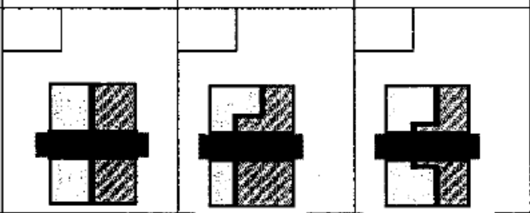
Assembly and disassembly processes

- *Req. 3.3: Additives, i.e. materials or fasteners, should not be used.* (Labelled D in the example.)

Select connection principles without separate fasteners or integrate/attach these later (step 8) into/to the components.

Step 6: Connection concept scheme

Combination identifier: C-Mech

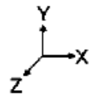
Standard connection principles (suitable for combinations with all joining concepts as there are planar (p); convex/concave Type A (ccA) and convex/concave Type B (ccB)) The connection principles are shown and described as 2D intersections of the connection. Geometrical relations are described by means of the axes of the 3D-orthogonal system.				
Id.	**Sketch** **P** / **ccA** / **ccB**	**Description of the structure;** **Necessary components' shape (Req. 1.3/1.4);** **Examples**	**Nr. of connectable comp. (Req. 2.1)**	**Nec. of sep. fasteners (Req. 3.3)**
A1		Locking is initiated directly at the components' interfaces. Mechanically interacting interfaces. Velcro structured interfaces.	2	No
A2		Locking is initiated at the surfaces of the components' contour. The fastener needs to be lead around the components' contour. Cable tie.	≥2	yes
A3				
A4		Locking is initiated at the components' faces parallel to the Y-axis. The fastener needs to be lead through the components. Working surfaces are to be provided. Bolted joint.		
A5		Locking is initiated at the components' faces parallel to the X-axis. The fastener needs to be lead around the components' contour. Cable tie.		
A6		Locking is initiated at the faces of the path through the components. The fastener needs to be lead through the components. Working surfaces are to be provided. Press fit.		
	...			

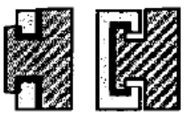
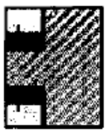
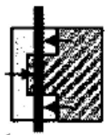
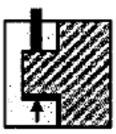
Crosses indicate connection principles selected in step 6

Figure C-10a: Connection principles scheme, continuation on next page

Special connection principles (suitable only for combinations with convex/concave Type B joining concept (ccB))

The connection principles are shown and described as 2D intersections of the connection. Geometrical relations are described by means of the axes of the 3D-orthogonal system.



Id.	Sketch	Description of the structure; Necessary components' shape (Req. 1.3/1.4); Examples	Nr. of connectable comp. (Req. 2.1)	Nec. of sep. fasteners (Req. 3.3)
B1		Locking is initiated at the components' interfaces parallel to the X-axis. Accurate interference between the interfaces needs to be provided. Press fit.		no
B2		Locking is initiated at the components' interfaces. Movements in X direction are restricted through the interfaces parallel to the Y-axis. Movements in Y direction are restricted through the interfaces parallel to the X-axis. Geometrical interaction of the interfaces needs to be realised. Snap fit, threads.	2	
B3		Locking is initiated at the components' interfaces which are parallel to the X-axis. The fastener is positioned between the interfaces. Accurate measurements of the components corresponding with the fastener need to be provided. Clamping collar		
B4		Locking is initiated at the components' faces parallel to the Y-axis. The fastener needs to be engaged with the convex component and needs to be lead outside of the concave component. Split pin, nut.	≥2	
B5		Locking is initiated at the surfaces of the path through the components. The fastener needs to be lead through both components. Split pin, wedge.		yes
B6	X 	Locking is initiated at the concave components' face parallel to the X-axis. The fastener needs to be lead around the concave component's contour. Vice, cable tie.	2	
B7		Locking is initiated at the components' interfaces parallel to the X-axis. The fastener needs to be lead through the concave component for contacting the convex component. Grub screw.		
	...			

Legend:	
Grey/hatched:	Components to be connected;
Full grey:	Initiation of locking (through components or fastener);
Arrows (→)	Possibility of force application.

Crosses indicate connection principles selected in step 6

Figure C-10b: Connection principles scheme, continuation

Step 7: Selecting connection concepts

Description:

In this step, connection concepts are systematically selected and eliminated, respectively, by means of selection criteria. The given selection criteria are divided into criteria for elimination (critera A-D in the documentation form of this step) and in those for preference (criteria E, F).

Documentation form:

- Selection chart (Figure C-11)

To Do:

- Open a selection chart and enter the connection concepts using their identifiers.

  As mentioned in step 6, the force field and material locked connection concepts are identical with their joining concepts. Hence take for these the identifier from the combination scheme, e.g. A-Wel.

  The identifier of each mechanically locked connection concept is to be generated through combining:

  o the identifier of the joining concept;
  o the identifier of the selected connection principle;

  e.g. B-Mech A2.

- If helpful for the selection process, enter additional selection criteria.
- Check the fulfilment of the criteria for each connection concept and mark this as follows:

  "+": pursue solution;
  "-": eliminate solution;
  "?": collect information (re-evaluable solution);
  "!": check requirements list for changes.

  If, in the suggested sequence, one criterion leads to the elimination of a connection concept, then the other criteria need not be applied any more.

- Decide upon the final decision as follows:

  "+", if all criteria are marked with "+".
  "-", if at least one elimination criteria is marked with "-".

  Recommendation for all other cases:

  o if a preference criteria is marked with "-", consider the importance of the fulfilment of the criteria;
  o if a criteria is marked with "?", consider the probability of the final fulfilment of the criteria;
  o if a criteria is marked with "!", consider whether it is possible to change the restricting requirement(s).

Step 7: Selection chart

Connection concept:	Criteria for elimination					Criteria for preference				Remarks (indications, reasons)	Final decision
	A: Compatible with the overall task and with one another.	B: Fulfil the demands of the requirements list.	C: Realisable in respect of performance, layout etc.	D: Expected to be within permissible costs.	...	E: Incorporate direct safety measures or introduce favourable ergonomic conditions.	F: Preferred by the designer's company.	G: Further additional functions can be fulfilled	...		
Enter connection concepts by their identifiers:	*Enter fulfilment of each criterion:* +: pursue solution; -: eliminate solution; ?: collect information (re-evaluable solution); !: check requirements list for changes.									*Enter remarks (indications, reasons):*	*Enter final decision: (+; -; ?; !)*
B-A2	+	+	+	+							+
B-A3	+	+	+	+							+
B-A5	+	+	+	+							+
C-A2	+	+	+	+							+
C-A3	+	+	+	+							+
C-A5	+	+	+	+							+
C-B6	–										–
E-A2	+	+	+	+							+
E-A3	+	+	+	+							+
E-A5	+	+	+	+							+
E-B6	+	+	+	+							+
G-A2	–										–
G-A3	–										–
G-B5	–										–
A-A2	+	+	+	+							+

Figure C-11: Selection chart

Step 8: Selecting / generating locking methods

This process step is described individually for each kind of locking.

Force field locked connection concepts (Not selected or generated in the example.)

Description:

For each selected connection concept final solutions are realised through allocating suitable locking methods. If the existing locking methods do not fulfil the assembly and/or disassembly process requirements, they can be modified or novel locking methods can be generated.

Documentation form:

- Final solution form (Figure C-13 – C-15)

Supportive information:

- Locking method lists (Appendix C.2.2)

  For each locking technology, i.e. vacuum, magnetism, a separate locking method list exist.

To Do:

- Use a separate final solution form for each resulting final solution.
- Select existing locking methods fulfilling those requirements of step 2 listed below and having been labelled with “D”. For this, use the locking method list corresponding with the considered locking technology. The listed number of locking methods is not exhaustive. Locking methods not listed can be added to the list. Modifications, i.e. small design changed retaining the locking method, can be done.
- Generate novel locking methods, if the existing locking methods are not sufficiently fulfilling those requirements of step listed below and having been labelled with “D”. For identifying possible field forces and their ways of activation and deactivation consult physics literature and specialists.
- Enter in each final solution form:
  - o identifier of the connection concept (identical to identifier of the combination);
  - o identifier of the selected, modified or designed locking method;
  - o sketch of the final solution resulting from applying the selected, modified or designed locking methods to the connection concept;
  - o short description of the assembly and disassembly processes;
  - o further useful and available information.

Requirements:

<u>Components</u>

- *Req. 1.1/1.2: The material of component 1 and/or component 2 should not be changed*.

Select methods which can be realised with the demanded/wished component materials. (Labelled D in the example.)

Connection function

- *Req. 2.1: Further components are to be attached through the connection.* (Only relevant for magnetism.)

Dimension the magnetic field so, that the demanded/wished number of components can be locked.

Assembly and disassembly processes

- *Req. 3.8/3.9: The assembly and/or disassembly subprocesses should be performed through identical triggers.*

If the force field

- o has the same direction as the joining movement,
- o is strong enough,
- o is already available before the components are locked,

then joining can be realised through applying the force field and assembling (joining and locking) is performed through only one trigger - the activation of the force field.
Separating in this case can be realised through releasing the force field (if planar joined), or through inverting the force field (if convex/concave joined) and disassembling (unlocking and separating) is performed through only one trigger - the deactivation of the force field.

- *Req. 3.10/3.11: Locking and/or unlocking should be performed manually without a tool.* (Labelled W in the example.)

The manually achievable triggers are movements with a restricted amount of force and access to the connection. Dimension the locking force so, that locking and/or unlocking can be applied manually or integrate/attach elements multiplying the force, e.g. release lever.

- *Req. 3.12/3.13: Locking and/or unlocking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously locking/unlocking "at the push of a button".*

Select locking methods where the force field can be activated and undone through switching an electric circuit.

Materially locked connection concepts (Not selected or generated in the example.)

The considered design process did not result in materially locked connection concepts. Thus, material locking methods were not selected or generated in this process.

Description:

From each selected connection concept final solutions are to be derived through determining suitable locking methods. If the existing locking methods do not fulfil the assembly and/or disassembly process requirements, they can be modified or novel locking methods can be generated.

Documentation form:
- Final solution form (Figure C-13 – C-15)

Supportive information:
- Locking method lists (Appendix C.2.2)

  For each locking technology, i.e. welding, soldering, gluing, a separate locking method list exist.

To Do:
- Use a separate final solution form for each resulting final solution.
- Select existing locking methods fulfilling those requirements of step 2 listed below and having been labelled with "D". For this, use the locking method list corresponding with the considered locking technology. The listed number of locking methods is not exhaustive. Locking methods not listed can be added to the list. Modifications, i.e. small design changed retaining the locking method, can be done.
- Generate novel locking methods, if the existing locking methods are not sufficiently fulfilling those requirements of step listed below and having been labelled with "D". For identifying possible cohesion and adhesion mechanisms and their ways of activation and deactivation consult chemistry literature and specialists.
- Enter in each final solution form:
  - o identifier of the connection concept (identical to identifier of the combination);
  - o identifier of the selected, modified or designed locking method;
  - o sketch of the final solution resulting from applying the selected, modified or designed locking methods to the connection concept;
  - o short description of the assembly and disassembly processes;
  - o further useful and available information.

Requirements:

<u>Components</u>

- *Req. 1.1/1.2: The material of component 1 and/or component 2 should not be changed.* (Labelled D in the example.)

Select methods which can be realised with the desired/wished component materials.

<u>Connection function</u>

- *Req. 2.4: The connection should work between specific temperatures.* (Labelled D in the example.)

Ensure that the connection is able to withstand the demanded/wished temperatures.

<u>Assembly and disassembly processes</u>

- *Req. 3.1: Locking should be achieved through movement and/or deformation.*

Cohesion can be realised through friction between the components to be connected, e.g. friction welding for components of plastic.

- *Req. 3.2: Unlocking should be achieved through movement and/or deformation.*

In welded connections where the original component interfaces no longer exist, unlocking through movements is only possible through cutting or breaking the components apart. Soldered/brazed connections can also be cut. However, the component interfaces are still existent so that it is also possible to cut the soldered/brazed and adhesive layer and keeping the component geometry.

- *Req. 3.3: Additives, i.e. materials or fasteners, should not be used.* (Only relevant for welding.) (Labelled D in the example.)

Select locking methods which do not require additional materials.

- *Req. 3.4: Geometry or molecular structure of the components should not change through locking and unlocking. This is a prerequisite for a connection that frequently can be assembled and disassembled.* (Only relevant for soldering/brazing and gluing). (Labelled D in the example.)

Prevent the occurrence of irreversible component changes like:

  - geometrical warping caused by heat impact;
  - materials remaining at the interfaces;
  - separate components at the soldered/brazed or adhesive layers.

- *Req. 3.11: Unlocking should be performed manually without a tool.* (Labelled W in the example.)

Consider the provision of tapered areas for enabling the connection to be unlocked with low forces by breaking the components apart. At welded connections, the connection will be broken apart at the component material. Soldered/brazed and glued connections can also be broken apart at the soldered/brazed or adhesive layer.

- *Req. 3.12: Locking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously locking "at the push of a button".*

About locking methods to be realised with unaligned triggers should be thought. For this, locking methods without additives are advantageous or those where the additives can be added when the components are joined. This is e.g. the case with soldering in an oven whereby the solder is added in the solid state when the components are joined. Specific kinematics or defined positions between tools and components are not required because the solder is liquefied and distributed under heat to the component interfaces.

- *Req. 3.13: Unlocking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously unlocking "at the push of a button".* (Only relevant for soldering/brazing and gluing).

Solder/braze is liquefied through heat transfer. Instead of removing the liquefied solder/braze through sucking devices to be moved in a defined path over the soldered/brazed layer, think about possibilities which are not requiring kinematics or defined positions, e.g. catch the liquefied solder/braze in a basin.

An adhesive layer can be dissolved through treatment with heat or UV-light. However, the difficulty is to pass these to the adhesive layer without damaging the components. Provided that the adhesive layer contains super paramagnetic particles, it can directly be heated through an alternating magnetic field.

Mechanically locked connection concepts

Description:

Before deriving from each connection concept final solutions through allocating suitable locking methods the locking technology has to be further specified. For this, the following mechanical locking technologies, i.e. Mech I, Mech II, Mech III, were defined (Figure C-12):

- Mech I restricts movements through geometrical interaction only. For unlocking, the geometrical interaction has to be interrupted.
- Mech II restricts movements through force only. For unlocking, the force has to be decreased.
- Mech III restricts movements through both geometrical interaction and force. For unlocking, both force and geometrical interaction has to be interrupted.

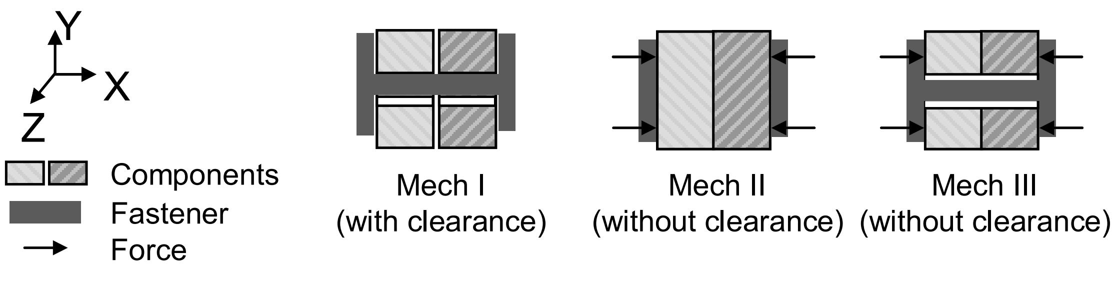


Figure C-12: Examples for Mech I, Mech II and Mech III.

Suitable locking methods are to be selected for each connection concept in accordance with its locking technology and connection principle. If the existing locking methods do not sufficiently fulfil the assembly and/or disassembly process requirements, they can be modified, e.g. by making little changes at fasteners for the adaptation to a tool but retaining their locking method, or novel locking methods can be generated.

Documentation form:
- Final solution form (Figure C-13 – C-15)

Supportive information:
- Locking method lists (Appendix C.2.2)

  For each connection principle, i.e. A1 to A6, B1 to B7, a separate locking method list exist. Each of these lists consist of two sections, namely the section: "selection of existing locking methods", and the section "generation of novel locking methods".

To Do:
- Use a separate final solution form for each resulting final solution.
- Specify further the locking technology of each connection concept through allocating Mech I, Mech II or Mech III.
- Select existing locking methods fulfilling those requirements of step 2 listed below and having been labelled with "D". For this, use the section "selection of existing locking methods" of the locking method list corresponding with the considered connection principle. The listed number of locking methods is not exhaustive. Locking methods not listed can be added to the list. Modifications, i.e. small design changes retaining the locking method, can be done.
- Generate novel locking methods, if the existing locking methods are not sufficiently fulfilling those requirements of step 2 listed below and having been labelled with "D". For this, use the section "generation of novel locking methods" of the locking method list corresponding with the considered connection principle.
- Enter in each final solution form:
  - identifier of the connection concept;
  - identifier of the selected, modified or generated locking method;
  - sketch of the final solution resulting from applying the selected, modified or generated locking method to the connection concept;
  - short description of the assembly and disassembly processes;
  - further useful and available information.

Requirements:

<u>Components</u>

- *Req. 1.3/1.4: A shape change of component 1 and/or component 2 is not possible or only under restrictions.* (Labelled D in the example.)

Apply only those locking methods which can be realised without shape changes or with shape changes corresponding to the requirements.

<u>Connection function</u>

- *Req. 2.1: More than 2 components should be connected.*

Select/generate methods with which the demanded/wished number of components can be locked.

- *Req. 2.2: To prevent movements or vibrations, the connection should be free of clearance.* (Labelled D in the example.)

Select/generate a locking method realising locking technology Mech II or Mech III. With locking technology Mech I clearance remains.

- *Req. 2.6: The unintended unlocking and separating of the components has highly negative effects, e.g. danger for live or health. Hence, higher safety standards against unlocking and separating of the components should be achieved.* (Labelled D in the example.)

The reliability can be influenced by the choice of locking technology. Mech I becomes unlocked, if the geometrical interaction fails, e.g. break of a component or fastener. Mech II becomes unlocked if the locking force increases. This can easily happen through e.g. different thermal extension in the connection area. With Mech III in this case geometrical interaction would remain.

<u>Assembly and disassembly processes</u>

- *Req. 3.3: Additives, i.e. materials or fasteners, should not be used.* (Labelled D in the example.)

Save separate fasteners through their integration into the components or their attachment to the components and ensure that joining and separating can still be performed. In this case, fastening is performed together with joining; unfastening with separating.

- *Req. 3.4: Geometry or molecular structure of the components should not change through locking or unlocking. This is a prerequisite for a connection that frequently can be assembled and disassembled.* (Labelled D in the example.)

Reject locking methods causing plastically deformation of the components.

- *Req. 3.5: Additives should withstand frequent locking and unlocking cycles.* (Labelled D in the example.)

Reject locking methods causing plastically deformation of the fasteners.

- *Req. 3.8/3.9: Assembly and/or disassembly subprocesses should be performed through identical triggers.*

The locking and unlocking triggers of each locking method are given in the locking method lists. In aiming for identical triggers, select locking methods with locking and/or unlocking triggers identical with the joining and/or separating triggers.
Integrate or attach fasteners to the components such that fastening is realised through the same trigger as joining and/or unfastening through the same trigger as separating.

- *Req. 3.10/3.11: Locking and/or unlocking should be performed manually without a tool.* (Labelled W in the example.)

The manually achievable triggers are movements with a restricted amount of force and access to the connection. Higher forces and/or better accessibility can be realised through an adequate design of the interacting component interfaces or the fasteners, i.e. integrating/attaching elements multiplying the force or transferring the movements, e.g. release cord, release lever.

- *Req. 3.12/3.13: Locking and/or unlocking should be realised through unaligned triggers, i.e. without the necessity of performing specific kinematics or providing defined positions between tools and components. This is a prerequisite for simultaneously locking/unlocking "at the push of a button".*

Choose unaligned triggers which are able to lock and/or unlock a connection. Some of them and the effects for transforming these into locking/unlocking triggers are listed in Table C-1. Consider also the modification of existing and the generation of novel locking methods.

Table C-1: Unaligned locking and unlocking triggers

Unaligned trigger:	**Effect to transform the unaligned trigger into the locking and/or unlocking trigger**	**Realisation depends on:**
Temperature	• Extension; • different extensions in one component through combination of different materials, e.g. bimetal; • extension caused by the change of the aggregation state; • change of consistency by the change of the aggregation state; • shape memory effect, i.e. material has different shapes at defined temperatures.	Material characteristics of the components and additives
Magnetism	Forces/movements resulting from the magnetic field	Material characteristics of the components and additives
Radio waves	Remote-controlled initiation of movements, i.e. mechanism with receiver, actuator and energy supply	Remote controlled transmissibility
Pressure	Shape change caused by changing the ambient pressure	Material characteristics and shape of the components and the additives
Liquids	Solubilisation of materials in liquids	Material characteristics of the liquids, the components and the additives
…	…	…

<u>Additional functions of the connection</u>

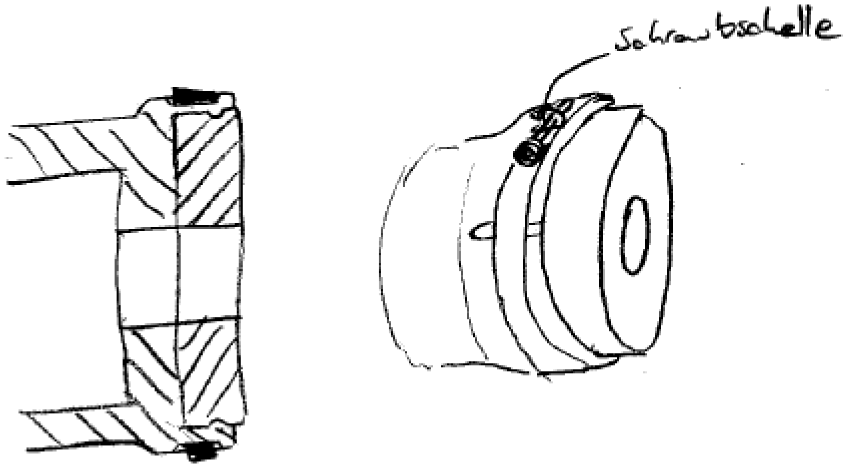
- *Req. 4.1: Overload protection should be provided, i.e. in case of overload the connection becomes disconnected in order to prevent damage of the components.* (Labelled W in the example.)

Determine the direction in which overload protection should be provided and realise that the connection is unlocked if overload occurs.

6

Final solutions (step 8)

Use for each final solution a separate form!
Number of the connection concept: E - B6 - 2



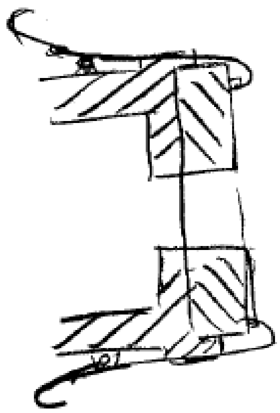
- Betonplatte wird mit Schraubschelle an Behälter befestigt

Figure C-13: Final solution form, application of locking method 2 of B6

7

Final solutions (step 8)

Use for each final solution a separate form!
Number of the connection concept: E - A3 3 (13:20)



- Klammer ober und unterhalb Kammer

Figure C-14: Final solution form, application of locking method no. 3 of A3

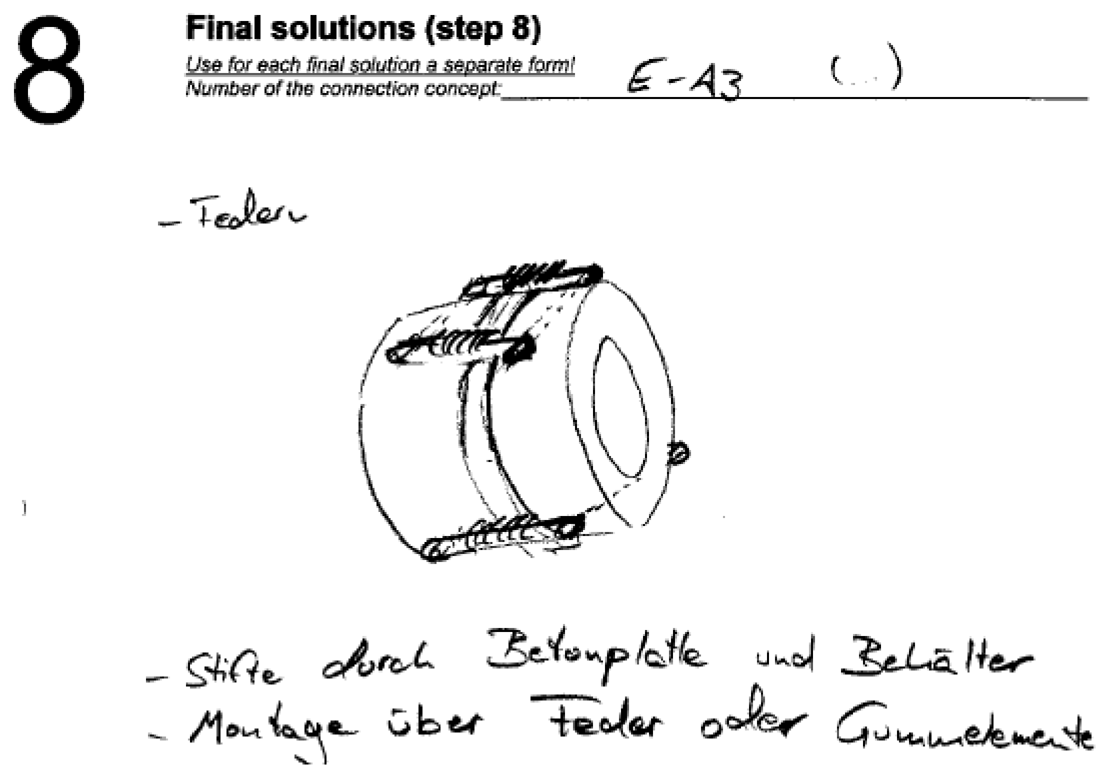


Figure C-15: Final solution form, modification of locking method no. 4 and 5 of A3

Step 9: Evaluating the selected and generated final solutions

Description:

In this step the best connections concerning their quality and suitability for the given task are identified through evaluating and rating the resulting final solutions with the evaluation chart.

Documentation form:

- Evaluation chart (Figure C-16)

To Do:

- Enter in the corresponding rows and columns of the evaluation chart:
  - o final solutions through their identifiers;
  - o evaluation criteria derived from requirements labelled with W in the requirements list;
  - o further relevant evaluation criteria;
  - o weighting factors of the evaluation criteria;

- Evaluate each final solution by means of the evaluation criteria and express their fulfilment by points with a range from 0 (unsatisfactory) to 4 (very good). Enter these into the corresponding cells of the evaluation chart. Multiply the values with the corresponding weighting factors and enter the results in the corresponding cells of the evaluation chart.
- Enter the sum of each column in the corresponding cells of the last row. Rank the final solutions according to their sum and determine the best connection. Commonly this is the one with the highest rank, i.e. highest sum.
- If a clear decision should be difficult, apply further evaluation methods. Some of these are described in detail by Pahl et al. [Pahl et al.-07, pp. 118].

Step 9: Evaluation chart

Evaluation chart																
Values: 4: very good, ideal; 3: good; 2: adequate; 1: just tolerable; 0: unsatisfactory																
No.	Evaluation criteria	*Factor of importance (weight)*	Final solutions (enter consecutive numbers):													
			A-A2		E-A3		E-A3 3		E-B6		C-A5		C-A3-3		B-A5 mod	
			val.	Weighted val.	*val.*	Weighted val	*val.*	Weighted val	*val.*	Weighted val	*val.*	Weighted val	*val.*	Weighted val	*val.*	Weighted val
1	Wenig Formveränderung	1x	4	4	4	4	2	2	3	3	3	3	1	1	2	2
2	einfache Montage	1x	3	3	2	2	3	3	3	3	1	1	3	3	1	1
3	wenig zusätzliche Bauteile	1x	1	1	1	1	3	3	3	3	3	3	3	3	3	3
4	Sicherheit (hoch)	3x	3	9	4	12	2	6	3	9	2	6	2	6	2	6
5	Erfüllung der Funktion	2x	2	4	4	8	3	6	3	6	3	6	3	6	3	6
6																
7																
8																
9																
10																
Σ				21		27		20		24		18		19		18

(3) (1) (4) (2) 5

Figure C-16: Evaluation chart

C.2 Supportive information

This section contains the supportive information of SYCONDE consisting of a locking technology list (Appendix C.2.1) and several locking method lists (Appendix C.2.2).

C.2.1 Locking technology list

	Kind of locking	Force field locking		Material locking			Mechanical locking
Req.-nr.	**Locking technologies:** **Criteria:**	**Vacuum**	**Magnetism**	**Welding**	**Soldering/ Brazing**	**Gluing**	**Mech I-III**
1.1/ 1.2	**Possible materials and material combinations.**	all	Ferromagnetic materials	The following material combinations are possible: • Steel (non-, low-, high-alloyed); • annealed cast iron, cast steel; • Al, Ti, Mg, and alloys; • Cu and Cu-alloys; • Ni and Ni-alloys, further heavy metals, refractory metals; • thermoplastics.	The following material combinations are possible: • Cu and Cu-alloys; • Ni and Ni-alloys; • ferrous material; • Co; • any steel; • Cr-steels, Cr-Ni-steels; • noble metals; • Al and Al-alloys with Mg and/or Si lower 2%; • Zn, Sb, Pb, Bi, Sn; • hard metals; • Cr. Mo, Ta, W, Nb; • Ti; • Zr, Be; • graphite, metallic oxide ceramics.	The following material combinations are possible: • Metals, i.e. aluminium, steel, phenolic resin, PA, ABS, PE, glas; • ceramics, glas-fiber reinforced plastic, e.g. GFK, rubber.	all
2.1	**Nr. of components which can totally be locked**	2	≥2	2			≥2
2.3	**Endurable stresses**	Connections can be stressed statically.		Connections can be stressed statically and dynamically.			

	Kind of locking	Force field locking		Material locking			Mechanical locking
Req.-nr.	**Locking technologies:** **Criteria:**	**Vacuum**	**Magnetism**	**Welding**	**Soldering/ Brazing**	**Gluing**	**Mech I-III**
3.1	**Necessary locking triggers.**	Movement.		Liquefaction of components' interfaces.	Addition of liquefied additives.		Movement and/or deformation.
3.3	**Necessity of additives, i.e. materials or fasteners.**	Generally not necessary.		Depends on the method if materials are necessary.	Material is always necessary.		Depends on the method if fasteners are necessary.
3.4	**Change of geometry or molecular structure of the components during locking and unlocking.**	Components are not changing.		Components are changing.	Components are not changing.		Depending on the locking method components are changing or not.
3.5	**Additives, i.e. materials or fasteners, should withstand frequent locking-unlocking cycles.**	If additives, i.e. fasteners, are necessary, they withstand frequent locking-unlocking cycles.		If additives, i.e. materials, are necessary they do not withstand frequent locking-unlocking cycles.	Additives, i.e. material, withstand frequent locking-unlocking cycles. Only the geometry of the additives changes.	Additives, i.e. materials, do not withstand frequent locking and unlocking cycles.	Depending on the locking method the additives, i.e. fasteners withstand frequent locking-unlocking cycles.
	Specific characteristics	…		Most versatile and effective technology. Applied to both, large and small technical products. Highest strength to weight ratio. Welding geometries are often complex.	Used for electrical components due to its good electrical conduction characteristics. Clearance of the soldering gap should be between 0.05 and 0.2 mm.	Critical influences: Humidity; UV light.	…

C.2.2 Locking method lists

The locking method lists for force field and material kinds of locking are arranged concerning the locking technology, in:

- Vacuum technology;
- Magnetism technology;
- Welding technology;
- Soldering/brazing technology;
- Adhesive technology.

The locking method lists for mechanical kind of locking are arranged concerning the connection principle, in:

- A1 Selection of existing locking methods;
- A1 Generation of novel locking methods;
- A2 Selection of existing locking methods;
- A2 Generation of novel locking methods;
- A3 Selection of existing locking methods;
- A3 Generation of novel locking methods;
- A4 Introduction;
- A4 Selection of existing locking methods;
- A4 Generation of novel locking methods;
- A5 Selection of existing locking methods;
- A5 Generation of novel locking methods;
- A6 Selection of existing locking methods;
- A6 Generation of novel locking methods;
- B1 Selection of existing locking methods;
- B1 Generation of novel locking methods;
- B2 Selection of existing locking methods;
- B2 Generation of novel locking methods;
- B3 Selection of existing locking methods;
- B3 Generation of novel locking methods;
- B4 Selection of existing locking methods;
- B4 Generation of novel locking methods;
- B5 Selection of existing locking methods;
- B5 Generation of novel locking methods
- B6 Selection of existing locking methods;
- B6 Generation of novel locking methods;
- B7 Selection of existing locking methods;
- B7 Generation of novel locking methods.

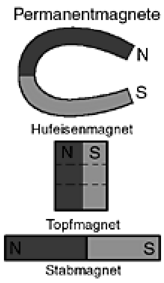
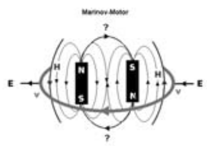
Vacuum technology

To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

Material of the components to be assembled (Req. 1.1, 1.2)	**Method**	**Locking process (Req. 3.8, 3.10, 3.12)**	**Unlocking process (Req. 3.9, 3.11, 3.19)**	**Examples**
Materials without penetrating pores.	1. Both components with cavity 	Var. 1: Joining of the components in a vacuum and exposition to ambient pressure.	Var. 1: Exposition of the connection to a vacuum environment.	Hemispheric balls of Magdeburg
		Var. 2: Joining of the components and provision of vacuum to the cavity.	Var. 2: Provide ambient pressure to the cavity.	
	2. One component with elastically vacuum cup 	Squeezing the air out of the vacuum cup after the components are joined.	Pull up the edge of the vacuum cup to provide ambient pressure.	Hooks for kitchen and bathroom
	3. One component with vacuum cup and lever for changing the volume of the cavity. 	Mechanical increasing of the cavity volume through turning the lever after the components are joined.	Mechanical decreasing of the cavity volume though turning the lever.	Short term connection for changing window glasses 

Magnetism technology

To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

Material of the components to be assembled (Req. 1.1, 1.2)	**Method**	**Locking process (Req. 3.8, 3.10, 3.12)**	**Unlocking process (Req. 3.9, 3.11, 3.19)**	**Examples**
One Permanent magnet, Ferro-magnetic materials	1. Combination of permanent magnetic component and ferromagnetic component.  	Alignment of components and move them together.	Movement of components apart from each other.	Furniture's door lock; Magnetic pins on a metallic cupboard.
Two permanent magnets	2. Combination of permanent magnetic components. 	Alignment of components around ≥90° so that the interference of different poles is more than 50%.	Alignment of components around ≥45° so that the interference of same poles is more than 50%.	[Patent DE 196 42 071].

Welding technology

To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

Possible materials and material combinations (Req. 1.1/1.2)	Method	Locking (L) and unlocking (UL) processes (Req. 3.2, 3.11)	Additives (components, materials, others) necessary for locking (Req. 3.3)	Necessary modi-fications at the components	Specific properties	Examples	Reference/ Literature
Fusion welding							
Non-alloyed, low alloyed steel, mainly carbon- and construction steel	Gas fusion welding (G)	**L**: Local melting through gas flame, elektode is provided manually **U**: Thermal cutting with the welding tools	Electrode of the same material as the components are, provided manually	Bare metal; components should be clean and free of grease in order to prevent inclusions	Tools can also be used for thermal cutting	Craftsmanship, installation works	Spur/Stöferle-86, pp. 243; Ruge-93, pp. 1
Alloyed, non-alloyed steel, cast iron, mainly construction steel	Flux cored metal-arc welding	**L**: Local melting through electric arc, inert gas for preventing oxidation	Downburning electrode of the same material as the components are		Low effort concerning tools, versatile applicability, mostly used welding method	Steel structuring engineering, bridge construction, mechanical engineering, shipbuilding, pipeline construction	Spur/Stöferle-86, pp. 258; Ruge-93, pp. 38
All materials of steel und nickel	Submerged welding (UP)	**L**: Local melting through electric arc, consumable electrode is continuously provided, powder for preventing oxidation	Melting electrode of the same material as the components are		Automated process, very high melting deposition rate, low flexibility	Very long seams in shipbuilding and the construction of pipelines and pressure vessels	Spur/Stöferle-86, pp. 263; Ruge-93, pp. 52
Non-, low- und high-alloyed steel, drawable nonferrous metals (Al-, Mg-, Cu- and Ni-alloys)	Gas shielded welding (MIG/MAG)	**L**: Local melting through electric arc, consumable electrode is continuously provided, inert gas for preventing oxidation	Melting electrode of the same material as the components are		High melting deposition rate	Steel construction, car production, construction of pipelines and tanks	Spur/Stöferle-86, pp. 270; Ruge-93, pp. 82
Nearly all metals, specially reactive and high-melting metals, stainless steel, aluminium	Tungsten inert gas welding	**L**: Local melting through electric arc, fuse wire is provided manually, Inert gas for preventing oxidation	Melting wire of the same material as the components are	Bare metal; components should be clean and free of grease in order to prevent inclusions	Low melting deposition rate, suitable for the fulfilment of high quality standards, material of the components is gently treated	Turbine manufacturing, nuclear technology, food industry, medical engineering, rooty welding of thick-walled components	Spur/Stöferle-86, pp. 277; Ruge-93, pp. 71
Steel of gamma phase iron and chrome-nickel, material of nickel, titan and zinc	Plasma welding	**L**: Local melting through plasma beam			Very thin seam, material of the components is very gently treated, high costs	Microtechnology, thick-walled tubes and tanks (chemical and aerospace engineering)	Spur/Stöferle-86, pp. 282; Ruge 93, pp. 78
Beam welding							
Different kinds of metal, combination of identical and different kinds of metal	Elektron beam welding (EBW)	**L**: Local melting under vacuum through electron beam		Bare metal; components should be clean and free of grease in order to prevent inclusions	Seam can be very precisely positioned, high welding speed, low deformation of the component, automated process, causes X-radiation, seaming areas with close tolerances, welding of deep seams possible	Aerospace and apparatus engineering, nuclear technology	Spur/Stöferle-86, pp. 289; Ruge-93, pp. 101
Different kinds of metal, combination of identical and different kinds of metal	Laser beam welding	**L**: Local melting through laser beam		Bare metal; components should be clean and free of grease in order to prevent inclusions	Seam can be very precisely positioned, high welding speed, low distortion, automated process, causes X-radiation, seaming areas with close tolerances, welding of deep seams possible	Car production, aerospace engineering, electrical industrie	Spur/Stöferle-86, pp. 293; Ruge-93, pp. 119

Possible materials and material combinations (Req. 1.1/1.2)	Method	Locking (L) and unlocking (UL) processes (Req. 3.2, 3.11)	Additives (components, materials, others) necessary for locking (Req. 3.3)	Necessary modi-fications at the components	Specific properties	Examples	Reference/ Literature
Pressure welding							
Sheet steel of any quality, combination of identical and different steel	Spot welding	**L**: Current is conducted through the components and results in punctual heating until the melting point; welding through pressure and temperature (high current)		Bare metal; components should be clean and free of grease in order to prevent inclusions	Short welding time, low deformation of the components, simple preparation of the butt, no additives necessary, automation is possible	Car production, industry and craftsmanship	Spur/Stöferle-86, pp. 300; Ruge-93, pp. 129
Low- and hifgh-alloyed steel, materials of nickel	Projection welding					Small parts in mass production, specially stamping parts	Spur/Stöferle-86, pp. 307; Ruge-93, pp. 153
Sheet steel, material which is contingently weldable	Continuous roller welding					Seal welds at tanks and pipes, manufacturing of geometrically simple parts resulting from combining profiles and coverplates	Spur/Stöferle-86, pp. 312; Ruge-93, pp. 155
Steel (diameter 50mm), copper, aluminium (diameter 15mm)	Resistance butt welding	**L**: Current is conducted through the components and results in punctual heating until the melting point; welding through pressure and temperature (high current)		Bare metal; components should be clean and free of grease in order to prevent inclusions	Requirements on the preparation of the material is high, complex and part- or rotation-symmetric components	Chain links, steering wheels, continuous wires	Spur/Stöferle-86, pp. 317; Ruge-93, p. 157
Thick steel and nonferrous metals	Flash butt welding	**L**: Current is conducted through the components and results in punctual heating until the melting point; welding through pressure and temperature (high current)			Automated process	Rail joints, rims, toolmaking, crankshafts	Spur/Stöferle-86, pp. 318; Ruge-93, pp. 158
Friction welding							
Many materials, combination of identical and different materials	Resistance butt welding	**L**: Melting through pressure and temperature (friction)		Bare metal; components should be clean and free of grease in order to prevent inclusions	Deformation and shortening of the components	Axle shafts, outlet valves, tools for shape cutting chipping technology, drill pipes, turbine wheels, track rollers	Spur/Stöferle-86, pp. 325; Ruge-93, pp. 174
Sheet metal, only materials with low strength, specially alloys of alumnium	Friction stir welding	**L**: Melting through frictional heat		Bare metal; components should be clean and free of grease in order to prevent inclusions	High process speed, low thermal load, high tool wear, high drive force	Longitudinal welds of tanks, panels, profiles for ships and cars	Spur/Stöferle-86, pp. 325
Arc pressure welding							
Low- and hoghalloyes steel (diameter 4-24mm), aluminium (diameter 6-12mm)	Stud welding	**L**: Local melting through electric arc		Bare metal; components should be clean and free of grease in order to prevent inclusions	Portable, manually operated tools or fully mechanised facilities	Assembly of bolts on sheet metal	Spur/Stöferle, 86, pp. 320; Ruge-93, pp. 168
Hollow profile of steel with thin walls	Arc pressure welding using a magneti-cally moved arc	**L**: Heating though electric arc, welding thorugh pressure				Dampers, fire extinguishers, filter housings, pipelines	Ruge-93, pp. 170
Steel, copper	Gas pressure welding	**L**: Heating of the components with burner, melting through pressure			Low investment necessary, welding process can be well observed, mobility	Rail tracks, overhead traction lines	Spur/Stöferle-86, pp. 323; Ruge-93, p. 172
Combination of identical and different materials	Cold pressure welding	**L**: Melting only with pressure			Very high pressure causes deformation of the components, welding at ambient temperatures	Contacting of conductors and connected parts	Spur/Stöferle-86, pp. 340; Ruge-93, pp. 185

Possible materials and material combinations (Req. 1.1/1.2)	**Method**	**Locking (L) and unlocking (UL) processes (Req. 3.2, 3.11)**	**Additives (components, materials, others) necessary for locking (Req. 3.3)**	**Necessary modi-fications at the components**	**Specific properties**	**Examples**	**Reference/ Literature**
Arc pressure welding							
Ductile metals; noble metals, aluminium, copper, titan, steel, silver, glas, thermoplasts, combinations of identical and different materials	Ultrasonic welding	**L**: Highfrequent oscillation and pressure		Bare metal; components should be clean and free of grease in order to prevent inclusions	At least one one component must be thin and light-weight	Semiconductor components and further electronic components	Spur/Stöferle-86, pp. 331; Ruge-93, pp. 183
Combinations of identical and different materials	Explosive welding	**L**: Detonation wave moves components with high speed resulting in welding of the components			Metals must have at least 5 % elasticity which cannot be reached with rollled materials	Shipbuilding: Intersection between steel body and the deck of aluminium	Ruge-93, pp. 194
Different metals	Diffusion welding	**L**: Heating of the components under high vacuum or intert gas, low pressure		Bare metal; components should be clean and free of grease in order to prevent inclusions	Surface quality must be very high, seam is partly invisible if identical materials are used	Aerospace engineering, assembly of carbid tips on tools	Spur/Stöferle-86, pp. 352; Ruge-93, pp. 190

Bibliography:

Spur/Stöferle-86 Spur, G.; Stöferle, Th.: *Handbuch der Fertigungstechnik*, Carl Hanser, München 1986

Ruge-93 Ruge, J.: *Handbuch der Schweisstechnik*, Springer, Berlin 1993

Soldering/Brazing technology

To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

Possible materials and material combinations (Req. 1.1/1.2)	**Method**	**Locking process (Req. 3.12)**	**Specific properties**	**Examples**	**Reference/ Literature**
Soldering (<450°C)					
Heavy metals: low alloyed steels (well solderable) high alloyed steels (difficult solderable) Cu, Ni, AG, Au, Pt (well solderable) Ta, Mo, W, V, NB (difficult solderable) Light alloys: Al, AL-alloys, Mg-alloys (well solderable) Be, Ti (difficult solderable) Choice of the solder with the referred literature.	**Soldering through solid bodies**				
	Hand soldering	Components are joined; solid solder is provided or the components' interfaces contain tin; soldering rod provides heat for the liquefaction of the solder/tin.	Very simple process	Electrical/electronic engineering, plum-bing, construction of apparatus, manu-facturing of loose articles	Ruge 93, p. 251; Atlas 06; Dorn
	Ultrasonic soldering	Components are joined, solid solder is provided, soldering rod provides heat for the liquefaction of the solder; Ultrasoundwaves makes the components free of oxid.	Tinning without flux	-	Ruge 93, p. 252; Dorn
	Roller soldering	Components are joined; liquid solder is provided; soldering area is heated through a roller rotating in the liquid solder.	For wetting with tinning and solder through a roller, a counter roller is necessary.	-	Ruge 93, p. 251; Dorn
	Soldering through liquids				
	Solder bath soldering	Components are joined; liquid solder is provided through digging the components into a soldering bath.	-	Conductor boards, tinning of components, radiators, heat exchangers	Ruge 93, p. 251; Atlas 06; Dorn
	Wave soldering	Components are joined; liquid solder is provided through holding the components into a soldering wave.	-	Conductor boards	Ruge 93, p. 252; Dorn
	Drag soldering	Components are joined; liquid solder is provided through digging the components into a soldering bath.	-	Conductor boards	Ruge 93, p. 252; Dorn
	Reflow soldering	Solder is added to components; components are joined; through a melting medium (oil) the solder is liquefied.	-	Conductor boards	Ruge 93, p. 252; Dorn
	Soldering through gas				
	Flame soldering	Components and solder are joined or solid solder is provided after the components are joined; liquefaction of the solder through a flame.	To prevent early oxidation, flame must not reach the soldering area with flux.	Manual Installation technique, auto-mated mass production	Ruge 93, p. 252; Atlas 06; Dorn
	Soldering with warmgas	Components and solder are joined; liquefaction of the solder through hot air produced through electricity.	-	-	Ruge 93, p. 252; Dorn 2
	Soldering in an gas oven	Components and solder are joined; liquefaction of the solder in an gas oven.	-	-	Ruge 93, p. 252; Dorn
	Vapour phase soldering	Components and solder are joined; liquefaction of the solder through providing steam of a hot liquid (condensation).	High process stability and reliability, big masses can reliably be warmed without overheating.	Conductor boards	Ruge 93, p. 253; Dorn
	Soldering through beam				
	Light beam soldering	Components and solder are joined; liquefaction of the solder through providing beams of coherent light.	Locally tight bounded warming is realised without physical contact, short soldering times, high facility costs	Stacked-on components, microtechnology, electronics	Ruge 93, p. 253; Dorn
	Laser beam soldering	Components and solder are joined; liquefaction of the solder through laser beam.			Ruge 93, p. 253; Dorn
	Soldering through electric current				
	Induction soldering	Components and solder are joined; liquefaction of the solder through providing altenating current.	Locally tight bounded warming is realised through low energetic efforts, short soldering times, good capability of automation	Simple rotation-symmetric components, e.g. dampers, brake pipes, appliance industry, car production.	Ruge 93, p. 253; Atlas 06; Dorn
	Resistance soldering	Components and solder are joined; liquefaction of the solder through resistant heating.	-	-	Ruge 93, p. 253; Dorn
	Soldering in an oven	Components and solder are joined; liquefaction of the solder through elektrically heated Stufen-, Durchlauf- oder Muffelöfen.	Soldering without causing stress and deformation through even warming, vacuum ovens required for high temperature soldering.	Appliance industry, car production.	Ruge 93, p. 253; Atlas 06; Dorn

Possible materials and material combinations (Req. 1.1/1.2)	Method	Locking process (Req. 3.12)	Specific properties	Examples	Reference/ Literature
Brazing (>450°C)					
Brazing though liquids					
St; aluminium alloys	Salt bath brazing	Components and solder are joined; liquefaction of the solder through dipping the components into a salt bath.	Specially suitable for the production of components with inaccessible solderings.	Heat exchangers, pipelines.	Ruge 93, p. 254; Atlas 06
St; aluminium alloys	Solder bath brazing	Components are joined; liquid solder is provided through digging the components into a soldering bath.	Except the case, that phosphoric brazings are used, a cover of the flux is necessary.	Heat exchangers, pipelines.	Ruge 93, p. 254; Atlas 06
Brazing through electric gas discharge					
Materials with zinc coated surface	Light arc brazing	Components are joined; solid solder is provided; light arc provides heat for the liquefaction of the solder.	-	Car bodies, thin sheet metals.	Ruge 93, p. 254
Brazing through gas					
CU, Ni, Ni-alloys, ferrous material, any steel, Co, Cr, chrome nickel steel, noble metals, Al, Al-alloys, hard metals, stellites, Mo, W, tantalum, Nb	Flame brazing	Components and solder are joined or solid solder is provided after the components are joined; liquefaction of the solder through a flame.	To prevent early oxidation, flame must not reach the soldering area with flux; differentiation between gap braze welding, gas braze welding and coating; suitable for mass production.	manual installation techniques, automated mass production.	Ruge 93, p. 254
Brazing through beam					
Materials of PC boards	Light beam brazing	Components and solder are joined; liquefaction of the solder through providing beams of coherent light.	-	-	Ruge 93, p. 254
	Laser beam brazing	Components and solder are joined; liquefaction of the solder through laser beam.	-	-	Ruge 93, p. 254
	Elektron beam brazing	Components and solder are joined; liquefaction of the solder through electronic beam.	Vakuum necessary.	-	Ruge 93, p. 255
Brazing through electric current					
CU, Ni, Ni-alloys, ferrous material, any steel, Co, Cr, chrome nickel steel, noble metals, Al, Al-alloys, hard metals, stellites, Mo, W, tantalum, Nb	Induction brazing	Components and solder are joined; liquefaction of the solder through providing mid- and high-frequency alternating current.	-	Simple rotation-symmetric components, e.g. dampers, brake pipes, aerospace, fine mechanics.	Ruge 93, p. 255; Atlas 06
	Resistance brazing	Components and solder are joined; liquefaction of the solder through resistant heating.	-	Mainly in mass production for brazing of components with simple geometries.	Ruge 93, p. 255; Atlas 06
CU, Ni, Ni-alloys, ferrous material, any steel, Co, Cr, chrome nickel steel, noble metals, Al, Al-alloys, hard metals, stellites, Mo, W, tantalum, Nb, Ti, zirconium, Be, graphite, ceramics of metal oxids	Brazing in an oven	Components and solder are joined; liquefaction of the solder through elektrically heated oven.	Brazing without causing stress and deformation through even warming, well suitable for mass production.	Aerospace, fine mechanics.	Ruge 93, p. 255; Atlas 06

Bibliography:
Ruge-93 Ruge, J.: *Handbuch der Schweisstechnik*, Springer, Berlin 1993
Atlas-06 http://www.konstruktionsatlas.de/verbindungstechnik/loeten/loeten_technologie.shtml; 29.11.2006
Dorn-06 Dorn, L.: *Verfahren der Füge- und Beschichtungstechnik 2*; Skript 2006, TU Berlin

Adhesive technology

To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

Possible materials and material combinations (Req. 1.1/1.2)	**Tempe-rature range [°C] (Req. 2.5)**	**Method**	**Additives (components, materials, others) necess. for locking (Req. 3.3)**	**Locking process (Req. 3.12)**	**Necessary modifications at the components to be assembled**	**Specific properties**	**Examples**	**Reference/ Literature**
Steel, aluminium, non-ferrous metal	-55 - 200	Reaction adhesive	Anaerobic adhesive	- Apply adhesive at one component's interface; - Join the components; -Curing by elimination of air.	Clean and degrease interfaces, mechanically abrasing as well as physical and chemical pre-treatments are possible afterwards.	Pressure shear strength up to 40 N/mm^2; Opt. roughness depth: Rz 1-3; Liquid at room temp. on air; Curing by isolating oxygen; Catalytic reaction with metal.	Shaft to collar connection; thread locking.	Atlas 06
Steel, aluminium, plastics (PMMA, POM, ABS, H-PVC, PS, NBR, IIR, EPDM, SBR), elastomers, leather, wood	up to +80	Reaction adhesive	Cyanacrylat adhesive (superglue)	- Apply adhesive at one component's interface; - Join the components; - Curing at humidity of 40-60%.		Quick handling; Short curing time (5-20 sec); Only for small-sized areas; Tensile shear strength: 20 N/mm.	Household	Atlas 06
Steel, aluminium, plastics, elastomers, leather, wood	-40 - +120	Reaction adhesive	Photo-initiated curing adhesive	- Apply adhesive at one component's interface; - Join the components; - Curing through irradiate UV-light (320-550nm wave length).		Epoxy and cyanacrylat adhesives; Tensile strength: up to 35 N/mm^2; Shear strength: up to 34 N/mm^2; Film thickness: up to 1 mm (small wave lengths), 5 mm (large wave length).	Medical technology	Atlas 06
Metal, glass, ceramics…	-55 - +180	Reaction adhesive	Silicon adhesive	- Apply adhesive at one component's interface; - Join the components; - Curing at humidity.		Good stress compensation between parts; Film thickness up to several millimetres possible; Very flexible after curing.	Sanitarian application; Sealing.	Atlas 06
	-30 - +160	Reaction adhesive	Epoxy resin (2 components)	- Mix and apply adhesive at one component's interface; - Join the components; - Curing through chemical reaction of two substances.		Consists of binder and hardener; Exothermic curing can cause stress in different components because of different heat expansion coefficients; Additional heat causes faster curing; Tensile shear strength: 30-40 N/mm^2.	-	Atlas 06
Plastics	up to 150 (tempor ary 250)	Reaction adhesive	Epoxy resin (1 component)	- Mix and apply adhesive at one component's interface; - Join the components; - Curing through heat or UV-light.		Can be conducting or isolating; Stress in components because of exothermic reaction (see above); Tensile shear strength: up to 29 N/mm^2; Tensile strength: up to 46 N/mm^2.	Boatbuilding	Atlas 06; Brockmann et al., p. 62
Metal, wood, plastics	not speci-fied	Reaction adhesive	Epoxy polyurethane adhesive (2 components)	- Mix and apply adhesive at one component's interface; - Join the components; - Curing through chemical reaction of two substances.		Consists of resin and hardener; Curing is mostly exothermic; Stress in components because of exothermic reaction (see above); Tensile shear strength: up to 8 N/mm^2; For large area bonding.	Furniture industry; Automotive (metal-plastic-bonding).	Atlas 06; Brockmann et al., pp. 67
Steel, aluminium, wooden and plaster panels,	not speci-fied	Reaction adhesive	Polyurethane adhesive (1 component)	Apply adhesive at one component's interface; Join the components; Curing at humidity.		Tensile strength up to 10 N/mm^2; Very flexible after curing; For large area bonding; Curing by humidity.	Furniture industry; Automotive industry (windows).	Atlas 06; Brockmann et al., pp. 66

Possible materials and material combinations (Req. 1.1/1.2)	**Tempe-rature range [°C] (Req. 2.5)**	**Method**	**Additives (components, materials, others) necess. for locking (Req. 3.3)**	**Locking process (Req. 3.12)**	**Necessary modifications at the components to be assembled**	**Specific properties**	**Examples**	**Reference/ Literature**
Wood, cork, textiles, rubber, PVC, metal	not speci-fied	Contact adhesive	Contact adhesive (containing solvent)	Apply adhesive to both components' interfaces; Let solvent evaporate (5-30 min); Join the components (the closer the better the diffusion process); Curing through evaporation of solvent.	Clean and degrease interfaces, mechanically abrading as well as physical and chemical pre-treatments are possible afterwards.	Elastic; Large area bonding possible; Creeps at high temperature.	Textile industry	Atlas 06; Brockmann et al., pp. 49
Foamed material, wood, cork, textiles, rubber, PVC, metal	not speci-fied		Contact adhesive (solvent free)	Apply adhesive to both parts; Let solvent (water) evaporate; Join the components (the closer the better the diffusion process); Curing through evaporation of solvent.		Large area bonding possible.	Laminated panels	Atlas 06; Brockmann et al., pp. 49
Metal	not speci-fied	Contact adhesive	Plastisoles	Apply adhesive at one component's interface; Join the components; Irradiate with heat (>100°C); Curing through evaporation of solvent.		Strong bonding at non-degreased surfaces; Cured adhesive is thermoplastic; Low heat and creeping resistance; Strength: up to 10 N/mm^2.	Car (body-in-white)	Atlas 06; Brockmann et al., pp. 34
Paper, metal, wood, plastics	not speci-fied	Hot melts	Thermoplastic resin	Melt adhesive (e.g. in pistol) and apply it at one component's interface; Join the components; Curing through physical setting by cooling.		Processing temp: 120°-240°C; Adheres also coated surfaces; Large area bonding possible.	Car (body-in-white); Civil engineering; Paper industry.	Atlas 06; Brockmann et al., p. 35, pp. 50
Paper, metal, wood, plastics	not speci-fied		Thermosetting, plastic	Melt adhesive (e.g. in pistol) and apply it at one component's interface; Join the components; Curing through chemical setting by cooling.		Processing temp: 120°-240°C; Adheres also coated surfaces; Large area bonding possible.		Brockmann et al., p. 35, pp. 50

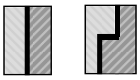
Bibliography:

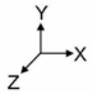
Atlas 06 http://konstruktionsatlas.de/verbindungstechnik/kleben/kleben.shtml Stand: 19.01.2007

Brockmann et al. Brockmann, W.; Geiss P. L.; Klingen, J.: *Klebstoffe, Anwendungen und Verfahren,* Wiley-VCH; Auflage: 1, 2005

Connection principle A1

Selection of existing locking methods





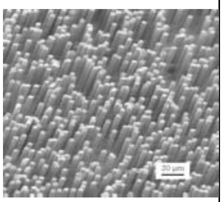
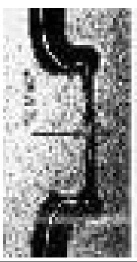
Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description: ccA

At connection principle A1 where components' interfaces are not situated opposite to each other, connections are only possible through geometrical interaction and hence only the locking parameters Mech I and Mech III can be realised.

To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Velcro® interface structure: 	*Locking*: Move the component interfaces together and thus realise geometrical interaction of the surface structure.	T(X) and/or T(-X)	*Unlocking*: Move component interfaces apart and thus tear the interacting surface structure apart.	T(-X) and/or T(X)	Interacting hooks and loops are damaged through unlocking; further locking is possible but endurable charge decreases; constricted number of locking and unlocking cycles.	One component surface consists of hooks, the other component surface consists of loops. Geometrical interaction between hooks and loops is realised through entanglement. Example: 
2. TOX® interface structure: 	*Locking*: Deform interface area of both components plastically at the same time and thus realise locking through geometry.	PD(ØX)	*Unlocking*: Cutting technologies.	PD(ØX)	Components interfaces change irreversibly through locking.	Geometrical interaction results from plastically deformation of the components interfaces. Applicable for sheet metal connections. Example: 
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A1

Generation of new locking methods

Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:
Components: Change the interface structure of one or both components or move the components relatively to each other.

Solutions for unlocking:
Components: Change the interface structure of one or both components or move the components relatively to each other.

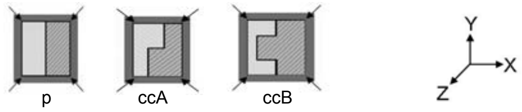
To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle A2

Selection of existing locking methods

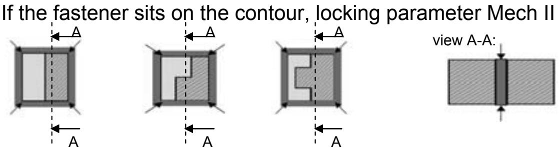


- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

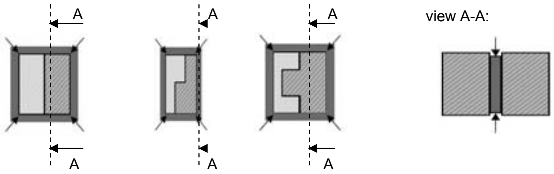
Description:

Depending on the fastener lead around the components the locking parameters Mech I, Mech II and Mech III can be realised.

If the fastener sits on the contour, locking parameter Mech II is realised:

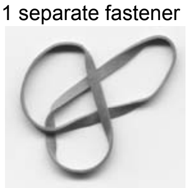


If the fastener sits in an incision of the contour, locking parameter Mech I and Mech III can be realised:



To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of separate fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Adhesive tape 1 separate fastener 	*Fastening and locking*: Move adhesive tape around components.	T(ØZ)	*Unlocking and unfastening*: Pull the tape away from the components.	T(ØZ)	Irreversible change of fasteners.	Locking force can be determined. Size can be individually adapted on the specific case. Specific application: packaging industry.
2. Rubber band 1 separate fastener 	*Fastening and Locking*: Adjust the length of the rubber band through folding; Deform the band elastically and move it over the components.	ED(ØZ) + T(-Z)	*Unlocking and Unfastening*: Expand the band elastically and remove it.	D(ØZ) + T(Z)	-	Different sizes. Can be adapted on the specific case. Connecting vibrating components. Universal application in household.
3. Plastic cord with clamp 2 separate fasteners: cord, latch.	Fastening: Move the cord around components; Provide the clamp.	T(ØZ)	Unlocking: Deform the clamp plastically.	PD(ØZ)	Irreversible change of fasteners.	Locking force can be determined. Size can be adapted individually on the specific case. Specific application: packaging industry.
	Locking: Tighten the entanglement, fix the position through plastically deformation of the clamp.	T(ØZ) + PD(ØZ)	Unfastening: Remove cord and clamp.	T(all directions)		

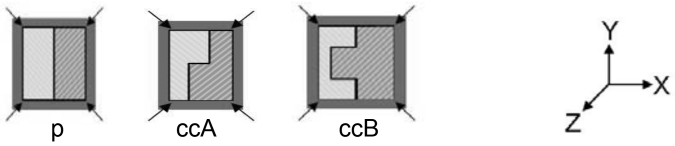
ID-number and locking method; Structure of separate fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
4. Cable tie 1 separate fastener 	Fastening (Var. 1): Move cable tie around components.	T(ØZ)	Unlocking (Var. 1): Move the pawl of the ratchet; move then the cable tie strap out of the eye.	T(ØZ)	-	Locking force can be determined. Standardised, different sizes. Specific application: connection of electric cables.
	Locking (Var. 1): Move cable end into the ear and tighten the entanglement.	T(ØZ)	Unfastening (Var. 1): Move the cable tie away from the components.	T(all directions)		
	Fastening (Var. 2): Move cable tie with the end already inserted in the ear over the components.	T(-Z)	Unlocking (Var. 2): Move the pawl of the ratchet; move the cable tie strap through the eye to increase the entanglement's diameter.	T(ØZ)	-	Locking force can be determined. Standardised, different sizes. Specific application: connection of electric cables.
	Locking (Var. 2): Tighten the entanglement.	T(ØZ)	Unfastening (Var. 2): Move the cable tie away from the components.	T(Z)		
5. Tension belt 1 separate fastener consisting of 6 parts. 	Fastening (Var. 1): Move the tension belt around the components.	T(ØZ)	Unlocking (Var. 1): Release the lever, turn it and move the belt out of the eye.	T(ØZ) + R(Z) + T(ØZ)	-	Locking force can be determined. Different sizes. Can be adapted on the specific case. Universal applications in transportation/ logistics.
	Locking (Var. 1): Move the belt end into the ear and tighten the entanglement through rotating the lever.	T(ØZ) + R(Z) + R(-Z)	Unfastening (Var. 1): Remove the tension belt.	T(all directions)		
	Fastening (Var. 2): Move tension belt with the end already inserted in the ear over the components.	T(-Z)	Unlocking (Var. 2): Release the lever, turn it and move the belt through the ear to increase the diameter of the entanglement.	T(ØZ) + R(Z) + T(ØZ)		
	Locking (Var. 2): Tighten the entanglement.	T(ØZ) + R(Z) + R(-Z)	Unfastening (Var. 2): Remove the tension belt.	T(Z)		
6. Textile cord with knot 1 separate fastener 	Fastening (Var. 1): Move cord around components.	T(ØZ)	Unlocking (Var. 1): Undo the knot.	T(all directions)	-	Locking force can be determined.
	Locking (Var. 1): Make a knot.	T(all directions)	Unfastening (Var. 1): Remove the cord.	T(all directions)		
	Fastening (Var. 2): Move cord with knot already prepared over the components.	T(Z) or T(-Z)	Unlocking (Var. 2): Untighten the knot and increase the entanglement diameter.	T(all directions) + T(ØZ)		
	Locking (Var. 2): Tighten the knot.	T(ØZ)	Unfastening (Var. 2): Remove the cord.	T(Z) or T(-Z)		

ID-number and locking method; Structure of separate fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
7. Clamping hose clamp: 1 separate fastener 	Fastening: Deform fastener elastically and move it over the concave component.	ED(ØZ) + T(Z) or T(-Z)	Unlocking: Deform fastener elastically.	ED(ØZ)	-	Standardised, different sizes. Specific application: connection of hoses in cooling systems.
	Locking: Undo the elastically deformation of the fastener.	Undo ED(ØZ)	Unfastening: Remove the fastener.	T(Z)		
8. Hose clamp with screw: 1 separate fastener consisting of 3 parts: entanglement, threaded bolt, tapped bush. 	Fastening: Move the fastener over the concave component.	T(Z) or T(-Z)	Unlocking: Rotate the screw in counter-clockwise direction.	R(ØZ)	-	Locking force can be adjusted.
	Locking: Rotate the screw in clockwise direction.	R(ØZ)	Fastening: Remove the fastener.	T(Z) or T(-Z)		
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A2

Generation of new locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Fastener: Close the fastener loop and/or decrease the cross section dimension of this loop.

Components: Increase the common cross section dimension of the components in the area of the fastener loop.

Solutions for unlocking:

Fastener: Increase the cross section dimension of the fastener loop and/or opening this loop.

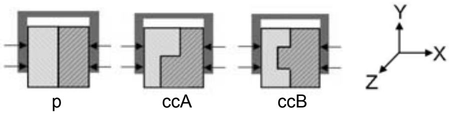
Components: Decrease the common cross section dimension of the components in the area of the fastener loop.

To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).
2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle A3

Selection of existing locking methods

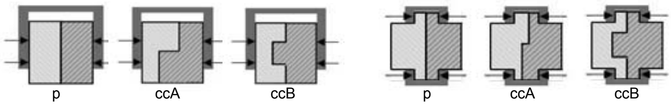


Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

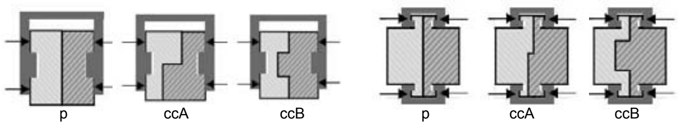
Description:

The locking technologies Mech I, Mech II and Mech III can be realised.

If the fastener sits on the contour as displayed in the following, Mech II can be realised:



If the fastener sits in an incision of the contour as displayed in the following, Mech I and Mech III can be realised:



To Do:

Select from the following list suitable locking methods fulfilling the defined requirements.

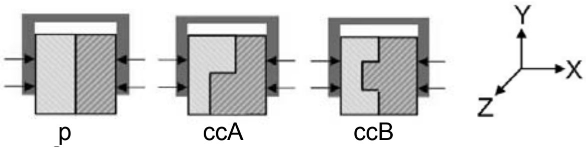
ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Screw clamp: 1 separate fastener consisting of 4 components. 	*Fastening*: Provide the fastener and move it over the components.	T(-Y)	*Unlocking*: Rotate the screw.	R(-X)	-	Adjustable locking force. Different sizes. Can be adapted on the specific case. Universal applications in craftsmanship for short-term fixation.
	Locking: Rotate the screw.	R(X)	*Unfastening*: Move the fastener apart.	T(ØX)		
2. Clamp/clip: 1 separate fastener consisting of 3 compontents. 	*Fastening*: Provide the fastener and deform it elastically.	T(-Y) +ED(X)	*Unlocking*: Deform the fastener elastically.	ED(X)	-	Different sizes. To be adapted to specific cases. Applied e.g. in offices for binding paper.
	Locking: Release the elastic deformation.	Undo ED(X)	*Unfastening*: Remove the fastener.	T(Y)		
3. Draw latch: 1 attached fastener consisting of 6 compontents. 	*Fastening*: Not necessary because the fastener is attached to one of the components.	-	*Unlocking*: Rotate the lever for releasing the locking force and move the hook out of the catch at the component.	R(-Z)+ T(Y)+ T(-X)	-	Different sizes. Universal applications in technical products for housings which need to be opened frequently, e.g. connector for air filter housing, hood latch.
	Locking: Move the fastener hook into the catch of the component and rotate the lever.	T(X) + T(Y) + R(+Z)	*Unfastening*: Not necessary due to fastener is attached to the component.	-		

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
4. Flexible T-handle latch: 1 separate fastener consisting of 1 component. 	*Fastening*: Provide the fastener and move its loop over one of the hooks of the components.	T(-Y) + T(-X)	*Unlocking*: Move the fastener loop away from one of the component hooks.	ED(-X) + T(Y)	-	Different sizes. Universal applications in technical products for housings which need to be opened frequently, e.g. connector for air filter housing, hood latch.
	Locking: Move the fastener loop over the other component's hook.	ED(-X) + T(-Y)	*Unfastening*: Move the loop of the fastener away from the other component hook and remove the fastener.	T(X) + T(Y)		
5. Hood-holder: 1 attached fastener consisting of 2 compontents. 	*Fastening*: Not necessary because the fastener is attached to one of the components.	-	*Unlocking*: Move the fastener's end out of the fork at the other component.	ED(-X) + R(-Z)	-	Different sizes. Universal applications in technical products for housings which need to be opened frequently, e.g. connector for air filter housing, hood latch.
	Locking: Move the fastener end into the fork at the other component.	R(Z) + ED(-X)	*Unfastening*: Not necessary because the fastener is attached to one of the components.	-		
…						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A3

Generation of new locking methods



- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:
Fastener: Decrease the distance between the interfaces with the components.
Components: Increase the component cross section dimension between the interfaces with the fastener.

Solutions for unlocking:
Fastener: Increase the distance between the interfaces with the components.
Components: Decrease the component cross section dimension between the interfaces with the fastener.

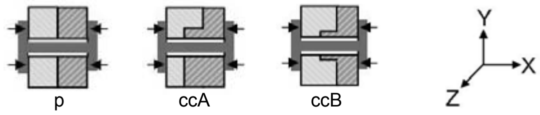
To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle A4

Introduction

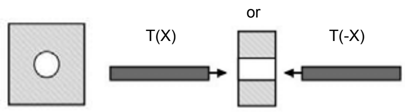


Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
The fastener pierces the components. Depending on the geometrical shape of the hole, fastener and components can be provided in different directions.

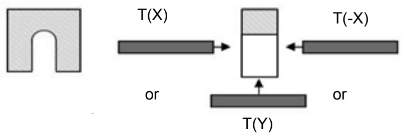
If the lead is a hole, two directions for fastening exist. The resulting locking technology can be Mech I and Mech III.

Lead is a hole:



If the lead is a notch, three directions for fastening/unfastening exist. The resulting locking technology is Mech II.

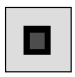
Lead is a notch:



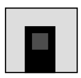
Possibilities to prevent rotatory movements around the fastener axes between components and fasteners:
-a locking force between the components and the fastener;

-fastener and component interact geometrically;

Component with hole:

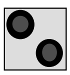


Component with notch:

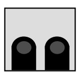


-more than one fastener is lead through the components.

Component with holes:

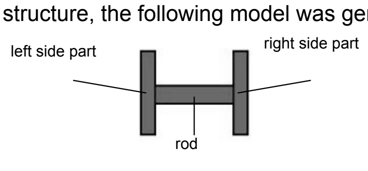


Component with notches:

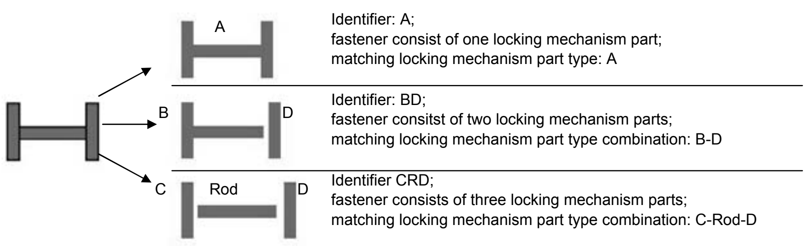


The fastener itself can consist of one or more components (all components can be integrated in one fastener or each of them can be separate, separate fastener components can also be integrated into the components). These circumstances are described through the fastener structure. The fastener structure has to be determined before the locking mechanism parts are selected.
The locking mechanism parts then are selected according to the structure of the fastener. To each structure matching locking mechanism parts are allocated, which together are forming the fastener.

For determining the fastener structure, the following model was generated:



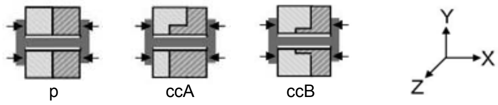
To Do:
Select suitable fastener structures:



According to the selected fastener structure select suitable locking methods.

Connection principle A4

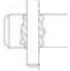
Selection of existing locking methods

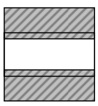


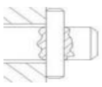
Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

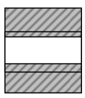
To Do:
Select from the following list suitable methods fulfilling the defined requirements and matching with the selcted fastener structure.

Fastener structure	**ID-number and locking method; Structure of necessary fasteners (Req. 3.3)**	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
		Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
A 	**A1. Rivet** 1 separate fastener consisting of one component. 	*Locking* : Plastically deformation	PD(X)	*Unlocking* : Cut the rivet head.	PD(X)	Rivet is plastically deformed through locking and unlocking.	Further locking mechanism part is not necessary.
	…						
B 	**B1. Plain bolt** 1 separate fastener consisting of one compo-nent. 	*Locking* : -	-	*Unlocking* : Plastically deformation.	PD(X)	-	Interface to D: to be adapted for matching with: D1; D2; D3; D4; D5; D6.
	B2. Bolt with snapper 1 separate fastener consisting of one compo-nent. 	*Locking* : -	-	*Unlocking* : Elastically deformation of the snap fit arms.	ED(ØX)	-	Interface to D: to be adapted for matching with: D1; D2; D3; D4; D5; D6.
	B3. Screw 1 separate fastener consisting of one compo-nent. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction.	R(X)	*Unlocking* : Rotate relatively to the other locking mechanism part in counter clockwise direction.	R(-X)	-	Interface to D: threat. Matches with: D7; D8; D9. Locking force adjustable.
	B4. Quick loading screw 1 separate fastener consisting of 3 components. 	*Locking* : Preload is increased through the lever.	R(ØX)	*Unlocking* : Preload is decreased through the lever.	R(ØX)	-	Interface to D: threat. Matches with: D7; D8; D9. Locking force adjustable. Quick application and release of the locking force through turning the lever.
	…						

Fastener structure	ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	Locking process (Req. 3.8, 3.10, 3.12)		Unlocking process (Req. 3.9, 3.11, 3.13)		Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)	Specific properties
		Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
C 	**C1. Removable bolt head I** 1 separate fastener consisting of 8 components. 	*Locking* : Move at the cap translatory towards the rod.	T(X)	*Unlocking* : Move at the cap translatory apart from the rod.	T(-X)	-	Matches with Rod. The removable bolt head I can be engaged and disengaged from the rod through translatory movement the cap.
	C2. Removable bolt head II 1 separate fastener consisting of 4 components. 	*Locking* : Lay segments in the rod and close the cable.	T(ØX), add heat or adhesive.	*Unlocking* : Cut the cables holding the segments.	PD(ØX)	Cable of segments are cut for unlocking	Matches with Rod. The removable bolt head II can be disengaged very fast through cutting the cable holding the segments in position. If the position is not provided any more, the segments disappear and the connection is unlocked.
	C3. Splint 1 separate fastener consisting of 1 component. 	*Locking* : Move the splint in the other locking mechanism part.	T(ØX)	*Unlocking* : Remove the splint from the rod.	T(ØX)	-	Matches with Rod.
	C4. Circlip 1 separate fastener consisting of 1 component. 	*Locking* : Move the circlip on the other locking mechanism part.	D(ØX) + T(x)	*Unlocking* : Remove the circlip from the rod.	D(ØX) + T(-X)		
	C5. Quarter turn receptacle 1 separate fastener consisting of 1 component. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction around 90° (quarter turn).	R(X)	*Unlocking* : Rotate relatively rod and receptacle counter clockwise around 90° (quarter turn).	R(-X)	-	Matches with Rod.
	C6. Dreika nut 1 separate fastener consisting of 1 component. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction around 120°.	R(X)	*Unlocking* : Rotate both side elements relatively to each other around 120° in counter clockwise direction.	R(-X)	-	Matches with Rod.

Fastener structure	**ID-number and locking method; Structure of necessary fasteners (Req. 3.3)**	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
		Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
C	**C7. Threaded nut** 1 separate fastener consisting of 1 component. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction.	R(X)	*Unlocking* : Rotate both side elements relatively to each other in counter clockwise direction.	R(-X)	-	Matches with Rod. Locking force adjustable.
	C8. Threaded "fast" nut 1 separate fastener consisting of 5 components. 	*Locking* (Var. 1): Rotate relatively to the other locking mechanism part in clockwise direction.	R(X)	*Unlocking* (Var 1): Rotate relatively to the other locking mechanism part in counter clockwise direction.	R(-X)	-	Matches with Rod. Locking force adjustable. Inner thread consists of two halves. Through changing their distance, two states can be achieved: closed and opened. Closed state: the halves form a thread which can engage and lock with any accordant outer thread through rotation. In the opened state the thread disengages from the outer thread and can be moved translatory over the outer thread.
		Locking (Var. 2): Move the nut halves via the cap on the rod. Once the nut halves hit the component, the cap is moved on the nut.	T(X)	*Unlocking* (Var. 2): Move the cap apart from the nut halves. Once the cup hits the nut halves, both, the nut halves and the cup will be removed by continuing the movement.	T(-X)	-	
	C9. Integrated inside thread 0 separate fastener, locking mechanism component is integrated in one of the components. 	*Locking* : Rotate relatively inner thread and other locking mechanism part in clockwise direction.	$R(X_R)$	*Unlocking* : Rotate relatively inner thread and other locking mechanism part in counter clockwise direction.	$R(X_L)$	-	Matches with B3, B4 and Rod. Locking force adjustable.
	…						
D	**D1. Removable bolt head I** 1 separate fastener consisting of 9 components. 	*Locking* : Move at the cap translatory towards the other locking mechanism part.	T(-X)	*Unlocking* : Move at the cap translatory apart from the other locking mechanism part.	T(X)	-	Matches with B1, B2 and Rod. Further specifics see C1.

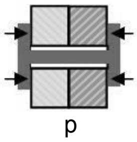
Fastener structure	**ID-number and locking method; Structure of necessary fasteners (Req. 3.3)**	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
		Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
D 	**D2. Removable bolt head II** 1 separate fastener consisting of 4 components. 	*Locking* : Lay segments in the other locking mechanism part and close the cable.	T(ØX), add heat or adhesive.	*Unlocking* : Cut the cables holding the segments.	PD(ØX)	Cable of segments are cut for unlocking	Matches with B1, B2 and Rod. For further specific properties see C2.
	D3. Splint 1 separate fastener consisting of 1 component. 	*Locking* : Move the splint In the other locking mechanism part.	T(ØX)	*Unlocking* : Remove the splint from the rod.	T(ØX)	-	Matches with B1, B2 and Rod.
	D4. Circlip 1 separate fastener consisting of 1 component. 	*Locking* : Move the circlip on the other locking mechanism part.	D(ØX) + T(-X)	*Unlocking* : Remove the circlip from the other locking mechanism part.	D(ØX) + T(X)	-	
	D5. Quarter turn receptacle 1 separate fastener consisting of 1 component**.** 	Locking: Rotate relatively to the other locking mechanism part in clockwise direction around 90° (quarter turn).	R(X)	Unlocking: Rotate relatively to the other locking mechanism part in counter clockwise direction around 90° (quarter turn).	R(-X)	-	
	D6. Dreika nut 1 separate fastener consisting of 1 component. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction around 120°.	R(X)	*Unlocking* : Rotate relatively to the other locking mechanism part in counter clockwise direction around 120°.	R(-X)	-	Matches with B1, B2 and Rod.
	D7. Threaded nut 1 separate fastener consisting of 1 component. 	*Locking* : Rotate relatively to the other locking mechanism part in clockwise direction.	R(X)	*Unlocking* : Rotate relatively to the other locking mechanism part in counter clockwise direction.	R(-X)	-	Matches with B3, B4 and Rod. Locking force adjustable.

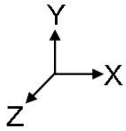
Fastener structure	**ID-number and locking method; Structure of necessary fasteners (Req. 3.3)**	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
		Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
D 	**D8. Threaded "fast" nut** 1 separate fastener consisting of 5 components. 	*Locking* (Var. 1): Rotate relatively to the other locking mechanism part in clockwise direction.	R(X)	*Unlocking* (Var 1): Rotate relatively to the other locking mechanism part in counter clockwise direction.	R(-X)	-	Matches with B3, B4 and Rod. Locking force adjustable. Further specifics see C8.
		Locking (Var. 2): Move the nut halves via the cap on the rod. Once the nut halves hit the component, the cap is moved on the nut.	T(-X)	*Unlocking* (Var. 2): Move the cap apart from the nut halves. Once the cup hits the nut halves, both, the nut halves and the cup will be removed by continuing the movement.	T(X)	-	
	D9. Integrated inside thread 0 separate fastener, locking mechanism component is integrated in one of the components. 	*Locking*: Rotate relatively inner thread and other locking mechanism part in clockwise direction.	R(X)	*Unlocking*: Rotate relatively inner thread and other locking mechanism part in counter clockwise direction.	R(-X)	-	Matches with B3, B4 and Rod. Locking force adjustable.
	…						
R(od)	**R1. Rod** 1 separate fastener Ends to be adapted on the locking mechanism components C and D.	*Locking*: Depends on locking trigger of the other locking mechanism part.	depends	*Unlocking*: Depends on unlocking trigger of the other locking mechanism part.	depends	-	The ends have to be adapted on each locking mechanism part type C and D and their combinations.

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A4

Generation of new locking methods

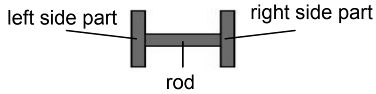




Planar or concave component to be connected — Interface
Planar or convex component to be connected — Possibility of locking force application
Fastener (Additive)

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

The fastener is described according to the following model:



<u>General solutions for locking and unlocking connections with locking technology Mech I, III</u>

Solutions for locking:

<u>Fastener</u>: Change fastener geometry through moving left or right side part relatively to each other or through increasing the cross section dimension of the left or right side part.

<u>Components</u>: Change component geometry through decreasing the cross section dimension of the fastener lead.

Solutions for unlocking:

<u>Fastener</u>: Change fastener geometry through moving left and right side part relatively to each other or through decreasing the cross section dimension of the left or right side part.

<u>Components</u>: Change component geometry through increasing the cross section dimension of the fastener lead.

<u>General solutions for locking and unlocking connections with locking technology Mech II</u>

Solutions for locking:

<u>Fastener</u>: Decrease the distance between the left and right side part.

<u>Components</u>: Increase the thickness between left and right side part.

Solutions for unlocking:

<u>Fastener</u>: Increase the distance between the left and right side part.

<u>Components</u>: Decrease the thickness between left and right side part.

To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Examples:

The components C1, C2, C8, D1, D2, D8 [A4 Selection of existing locking methods] displayed in Figure 1 are fasteners generated for supporting locking and/or unlocking. These specific fasteners are basing on the general solution shown in Figure 2.

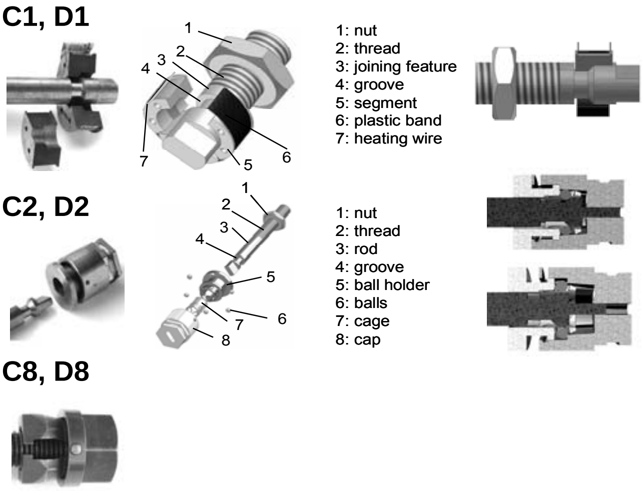


Figure 1: Specific solutions

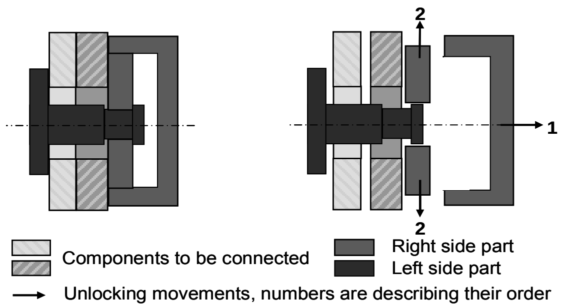
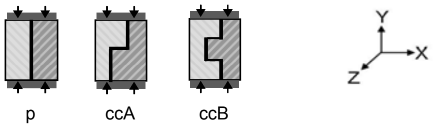


Figure 2: General solution

Connection principle A5

Selection of existing locking methods



- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- → Possibility of locking force application

Description:
With A5, only the locking parameter Mech II can be realised.

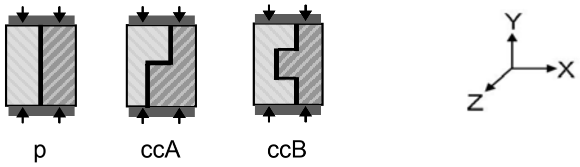
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	Locking process (Req. 3.8, 3.10, 3.12)		Unlocking process (Req. 3.9, 3.11, 3.13)		Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)	Specific properties
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Plastic cord with clamp 2 separate fasteners: cord, clamp. 	*Fastening*: Move the cord around components; Provide the clamp.	T(ØX)	*Unlocking*: Deform the clamp plastically.	PD(ØX)	Irreversible change of fasteners.	Locking force can be determined. Size can be adapted individually on the specific case. Specific application: packaging industry.
	Locking: Tighten the entanglement, fix the position through plastically deformation of the clamp.	T(ØX) + PD(ØX)	*Unfastening*: Remove cord and clamp.	T(all directions)		
2. Clamping hose clamp 1 separate fastener 	*Fastening*: Deform fastener elastically and move it over the concave component.	ED(ØX) + T(X)	*Unlocking*: Deform fastener elastically.	ED(ØX)	-	Standardised, different sizes. Specific application: connection of hoses in cooling systems.
	Locking: Undo the elastically deformation of the fastener.	Undo ED(ØX)	*Unfastening*: Remove the fastener.	T(-X)		
3. Hose clamp with screw 1 separate fastener consisting of 3 parts: entanglement, threaded bolt, tapped bush. 	*Fastening*: Move the fastener over the concave component.	T(X)	*Unlocking*: Rotate the screw in counter-clockwise direction.	R(ØX)	-	Locking force can be adjusted.
	Locking: Rotate the screw in clockwise direction.	R(ØX)	*Fastening*: Remove the fastener.	T(X)		
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A5

Generation of new locking methods



- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking :

Fastener: Decrease the distance between the interfaces with the components.

Components: Increase the component cross section dimension between the interfaces with the fastener.

Solutions for unlocking :

Concave component: Increase the distance between the interfaces with the components.

Convex component: Decrease the component cross section dimension between the interfaces with the fastener.

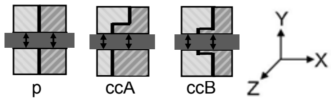
To Do:

1. Generate general solutions, determining
- the area where and the directions through which locking and/or unlocking should be realised;
- the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle A6

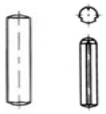
Selection of existing locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
With A6, only the locking parameter Mech II can be realised.

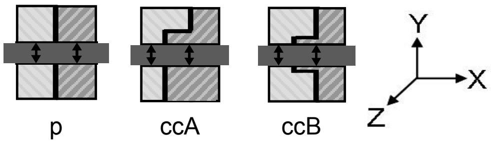
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Cylindrical, tapered, grooved pin 1 separate fastener consisting of 1 part. 	*Fastening*: Move the fastener to the components.	T(X) or T(-X)	*Unlocking*: Move the fastener out of the component hole.	T(X) or T(-X)	-	-
	Locking: Move the fastener completely into the component hole.	T(X) or T(-X)	*Unfastening*: Move the fastener apart from the components.	T(X) or T(-X)		
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle A6

Generation of new locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Fastener: Increase the distance between the interfaces with the components.

Components: Change component geometry through decreasing the cross section dimension of the fastener lead.

Solutions for unlocking:

Fastener*:* Decrease the distance between the interfaces with the components.

Components: Change component geometry through increasing the cross section dimension of the fastener lead.

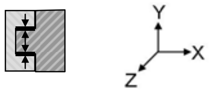
To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

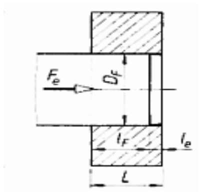
Connection principle B1

Selection of existing locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
Due to the component interfaces are situated opposite to each other, locking is realised through the transmission of locking forces between these interfaces. As geometrical interaction is not necessary, the locking parameter Mech II is realised. Suitable locking mechanisms for transmitting locking forces between the interfaces should be selecte
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

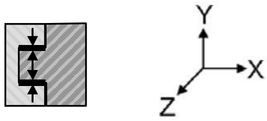
ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)** Due to joining and locking here mostly is one combined step, both processes are considered in common.		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)** Because unlocking and separating here mostly are one combined step, both processes are considered in common.		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Lego (interference fit): no fastener 	*Joining and Locking*: Move concave and convex components together.	T(X) and/or T(-X)	*Unlocking and Separating*: Move the components apart.	T(-X) and/or T(X)	-	The force which is transmitted between the components results from the interference between hole and pin diameter and the elasticity of the material. The transmitted force leads to friction force between the component interfaces. Convex/concave interference must be of cylindrical geometry. Applied for shaft-hub connections.
2. Interference fit: no fastener 	*Joining and Locking* (Var. 1): Move under high forces the concave component on the convex component.	T(X) and/or T(-X)	*Unlocking and Separating* (Var. 1): Move both components with high forces apart from each other.	T(-X) and/or T(X)	-	The force which is transmitted between the components results from the interference between hole and pin diameter and the elasticity of the material. The transmitted force leads to friction force between the component interfaces. Convex/concave interference must be of cylindrical geometry. Applied for shaft-hub connections.
	Joining and Locking (Var. 2): Cool the convex component; Move the concave component on the convex component.	Cool the convex com ponent; T(X) and/or T(-X).	Unlocking and Separating (Var. 2): Cool the convex component; Move both components apart from each other.	Cool the convex com ponent; T(-X) and/or T(X).		
	Joining and Locking (Var. 3): Heat the concave component; Move the concave component on the convex component.	Addition of heat; T(X) and/or T(-X).	*Unlocking and Separating* (Var. 3): Heat the concave component; Move both components apart from each other.	Addition of heat; T(-X) and/or T(X).		

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)** Due to joining and locking here mostly is one combined step, both processes are considered in common.		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)** Because unlocking and separating here mostly are one combined step, both processes are considered in common.		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
3. Dreika circle wedge interference fit 	*Joining*: Move the concave on the convex component.	T(X)	*Unlocking*: Rotate the convex and concave components relatively to each other in counter clockwise direction.	R(-X) and/or R(X)	-	Through the wedges on the circumference of the interfaces the transmitted locking force between both components changes through relative rotation of the components. Through relative rotation in clockwise direction the transmitted locking force increases, through rotation in counter-clockwise direction it decreases.
	Locking: Rotate the convex and concave components relatively to each other in clockwise direction.	R(X) and/or R(-X)	*Separating*: Remove the concave component from the convex one.	T(-X)		
…						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B1

Generation of new locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Concave component: Decrease the cross section dimension of the interface with the convex component.

Convex component: Increase the cross section dimension of the interface with the concave component.

Both, convex and concave component: Decrease the clearance between the component interfaces; move the components relatively to each other according to specific kinematics.

Solutions for unlocking:

Concave component: Increase the cross section dimension of the interface with the convex component.

Convex component: Decrease the cross section dimension of the interface with the concave component.

Both, convex and concave component: Increase the clearance between the component interfaces; move the components relatively to each other according to specific kinematics.

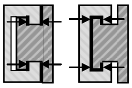
To Do:

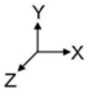
1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B2

Selection of existing locking methods

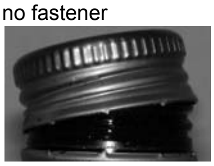




Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
B2 works with geometrical interaction. Connections with clearance are possible. Through applying a locking force, clearance can be prevented. Hence the locking parameters Mech I and Mech III can be realised.
Suitable locking mechanisms are to be selected through which the components can be locked at their interfaces.

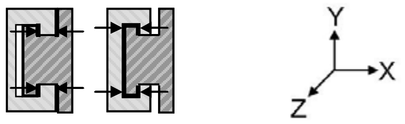
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)** Due to joining and locking here mostly is one combined step, both processes are considered in common.		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)** Because unlocking and separating here mostly are one combined step, both processes are considered in common.		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Snap fit interface: no fastener 	*Joining and Locking*: Move the components together.	T(X) and/or T(-X)	*Unlocking and Separating*: Deform the snap arms elastically and move the components apart.	ED(ØX) + T(-X) and/or T(X)	-	
2. Threaded interface: no fastener 	*Joining and Locking*: Move the components together and rotate them relatively to each other in clockwise direction.	T(X) + R(X)	*Unlocking and separating*: Rotate the components relatively to each other and move them apart in counter-clockwise direction.	R(-X) + T(-X)	-	Locking force can be adjusted.
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B2

Generation of new locking methods



- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Concave component: Decrease the cross section dimension of the interface with the convex component.

Convex component: Increase the cross section dimension of the interface with the concave component.

Both, convex and concave component: Decrease the distance between the component interfaces; move the components relatively to each other according to specific kinematics.

Solutions for unlocking:

Concave component: Increase the cross section dimension of the interface with the convex component.

Convex component: Decrease the cross section dimension of the interface with the concave component.

Both, convex and concave components: Increase the distance between the component interfaces; move the components relatively to each other according to specific kinematics.

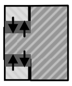
To Do:

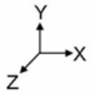
1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B3

Selection of existing locking methods

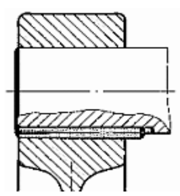
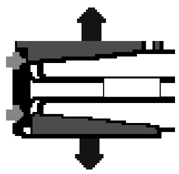
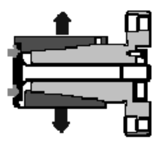


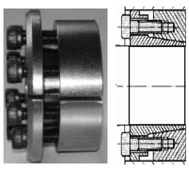
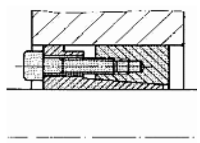


- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

Description:
If the component interfaces are situated opposite to each other, locking can be realised through the transmission of forces between the interfaces situated opposite to each other. The locking forces here are realised through fasteners sitting between the opposite situated interfaces. Due to geometrical interaction is not available, the locking parameter Mech II is realised.

To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Longitudinal pin 1 separate faster consisting of one part. 	*Fastening*: Move the fastener into the slot between convex and concave component.	T(X)	*Unlocking and unfastening*: Pull the fastener out of the slot.	T(-X)	-	Example: 
	Locking: Press the fastener into the slot.	T(X)				
2. Clamping sleeve 1 fastener consisting of 2 parts: clamping sleeve, threaded bolt. 	*Fastening*: Move the fastener between the components; Catch the thread.	T(X) + R(X)	*Unlocking*: Reduce the locking force through rotating the bolt in counter-clockwise direction.	R(-X)	-	Locking force can be adjusted. Convex component interface needs to be conical, the concave interface needs to be cylindrical. Through the screw, the sleeve is moved on the convex component. The cone leads to an increasing diameter of the fastener resulting in locking force between the components. Example: 
	Locking: Rotate the bolt in clockwise direction until the necessary locking force is achieved.	R(X)	*Unfastening*: Rotate the bolt in counter-clockwise direction out of the thread; Remove the fastener from the components.	R(-X) + T(-X)		

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
3. Clamping collar 1 fastener consisting of 10 parts: inside ring, outside ring, 8 (number depends on the fastener diameter) threaded bolts. 	*Fastening*: Move the fastener onto the convex component.	T(X)	*Unlocking*: Reduce the locking force through rotating the bolts in counter-clockwise direction.	8*R(-X)	-	Locking force can be adjusted. Convex/concave interference must be of cylindrical geometry. Applied for shaft-hub connections. In- and outside ring are moved towards with the screws. Through the interaction of the ring cones, the diameter of the fastener increases resulting in locking force between the components. Example: 
	Locking: Rotate the bolts in clockwise direction until the necessary locking force is achieved.	8*R(X)	*Unfastening*: Move the fastener away from the concave component.	T(-X)		
3. Pressure sleeve 1 fastener consisting of 7 parts: 1 collar, 6 (number depends on the fastener diameter) threaded bolts. 	Fastening: Move the fastener onto the convex component.	T(X)	Unlocking: Reduce the locking force through rotating the bolts in counter-clockwise direction.	6*R(-X)	-	Locking force can be adjusted. Convex/concave interference must be of cylindrical geometry. Applied for shaft-hub connections. The fastener ends are moved towards each other through the screws resulting in an increased diameter of the fastener. This in turn results in locking force between the components.
	Locking: Rotate the bolts in clockwise direction until the necessary locking force is achieved.	6*R(X)	Unfastening: Move the fastener away from the convex component.	T(-X)		
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B3

Generation of new locking methods

Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:
Fastener: Increase the distance between the interfaces with the convex and concave component.
Concave component: Decrease the cross section dimension of the interface with the fastener.
Convex component: Increase the cross section dimension of the interface with the fastener.

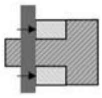
Solutions for unlocking:
Fastener: Decrease the cross section dimension between the interfaces with the convex and concave component.
Concave component: Increase the cross section dimension of the interface with the fastener.
Convex component: Decrease the cross section dimension of the interface with the fastener.

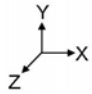
To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).
2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B4

Selection of existing locking methods



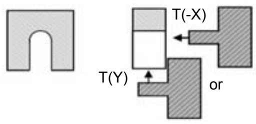


▢	Planar or concave component to be connected	■	Interface
▨	Planar or convex component to be connected	→	Possibility of locking force application
■	Fastener (Additive)		

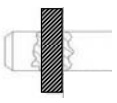
Description:
The convex component is lead through the concave component. Depending on the geometrical shape of the concave component, the convex component can be provided in one or more directions.

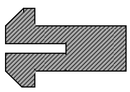
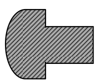
If the lead is a hole, only two directions exist for joining the convex and the concave component. If the lead is a hole, the resulting locking parameter can be Mech I and Mech III.

If the lead is a notch, three or more (depending on the specific notch geometry) directions exist for joining the convex and the concave component. If the lead is a notch, the resulting locking parameter is Mech II.



To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

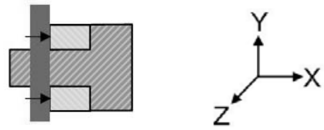
ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	Joining and locking process (Req. 3.8, 3.10, 3.12)		Unlocking and separating process (Req. 3.9, 3.11, 3.13)		Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)	Specific properties
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Splint 1 separate fastener consisting of 1 part. 	*Fastening and locking*: Move the fastener on the rod.	T(ØX)	*Unlocking and unfastening*: Move the fastener away from the rod.	T(ØX)	-	-
2. Circlip 1 separate fastener consisting of 1 part. 	*Fastening and locking*: Move the fastener on the rod.	T(ØX)	*Unlocking and unfastening*: Move the fastener away from the rod.	T(ØX)	-	-
3. Quarter turn receptacle 1 separate fastener consisting of 1 part. 	*Fastening*: Provide the fastener.	T(X)	*Unlocking*: Rotate fastener about 90° (quarter turn) relatively to the convex component in counter clockwise direction.	R(-X)	-	-
	Locking: Rotate fastener about 90° (quarter turn) relatively to the convex component in clockwise direction.	R(X)	*Unfastening*: Remove the fastener.	T(-X)		

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	Joining and locking process (Req. 3.8, 3.10, 3.12)		Unlocking and separating process (Req. 3.9, 3.11, 3.13)		Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)	Specific properties
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
4. Dreika nut 1 separate fastener consisting of 1 part. 	*Fastening*: Provide the fastener.	T(X)	*Unlocking*: Rotate fastener about 120° relatively to the convex component in counter clockwise direction.	R(-X)	-	-
	Locking: Rotate fastener about 120° relatively to the convex component in clockwise direction.	R(X)	*Unfastening*: Remove the fastener.	T(-X)		
5. Threaded nut 1 separate fastener consisting of 1 part. 	*Fastening*: Provide the fastener.	T(X)	*Unlocking*: Rotate fastener relatively to the convex component in counter clockwise direction.	R(-X)	-	Locking force can be adjusted.
	Locking: Rotate fastener relatively to the convex component in clockwise direction.	R(X)	*Unfastening*: Remove the fastener.	T(-X)		
6. Threaded fast nut 1 separate fastener consisting of 5 parts. 	*Fastening* (Var. 1): Provide the fastener.	T(X)	*Unlocking* (Var. 1): Rotate fastener relatively to the convex component in counter clockwise direction.	R(-X)	-	Adjustable locking force. Inner thread consists of two halves. Through changing their distance two states can be achieved: closed and opened. Closed state: the halves form a thread which can engage and lock with any accordant outer thread. In the opened state the thread disengages from the outer thread and can be moved translatory over the outer thread.
	Locking (Var. 1): Rotate fastener relatively to the convex component in clockwise direction.	R(X)	*Unfastening* (Var. 1): Remove the fastener.	T(-X)		
	Fastening and Locking (Var. 2): Move the fastener on the convex component.	T(X)	*Unlocking and unfastening* (Var. 2): Move the fastener apart from the convex component.	T(-X)		
7. Snapper, integrated in the convex component 0 separate fastener. 	*Joining and Locking*: Moving the convex component into the concave one results in elastically deformation of the snap fit arms.	T(-X) + ED(ØX)	*Unlocking and separating*: Elastically deformation of the snap fit arms and moving the convex component apart.	ED(ØX) + T(X)	-	-
8. Deformed end of the out poking part of the convex component. 0 separate fastener. 	Locking: Plastically deformation	PD(ØX)	Unlocking: Cut the rivet head.	PD(ØX)	Through unlocking, rivet will be plastically deformed.	-
…						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B4

Generation of new locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

General solutions for locking and unlocking connections with connection parameter Mech I, III
(The fastener lead through the concave component is a hole):
Solutions for locking :
Fastener: Increase the fastener cross section dimension.
Concave component: Decrease the cross section dimension of the concave component hole.
Both, fastener and convex component: Move fastener and convex component relatively to each other according to specific kinematics.

Solutions for unlocking :
Fastener: Decrease the fastener cross section dimension
Concave component: Increase the cross section dimension of the concave component hole.
Both, fastener and convex component: Move fastener and convex component relatively to each other according to specific kinematics.

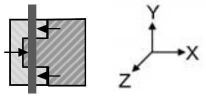
General solutions for locking and unlocking connections with connection parameter Mech II
(The fastener lead through the concave component is a notch):
Solutions for locking :
Fastener and convex component: Decrease the distance between the fastener and the interface between convex and concave component.
Concave component: Increase the thickness between the interfaces with the fastener and the convex component.

Solutions for unlocking :
Fastener and convex component: Increase the distance between the fastener and the interface between convex and concave component.
Concave component: Decrease the thickness between the interfaces with the fastener and the convex component.

To Do:
1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).
2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B5

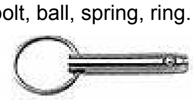
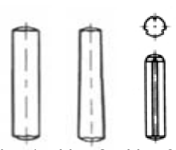
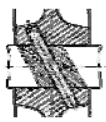
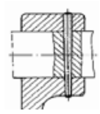
Selection of existing locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
Due to the fact that the fastener penetrates both components, locking is affected through geometrical interaction. Hence, with connection principle B5 only the locking parameters Mech I and Mech III can be realised.

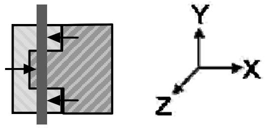
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Bolt with spring split pin 1 separate fastener consisting of 2 parts: bolt, spring split pin. 	Fastening and locking: Move the fastener into the hole; move a splint into the hole at the end of the bolt.	T(-Y) + T(ØY)	Unlocking and unfastening: Move the splint out of the bolt's hole; move the bolt out of the hole.	T(ØY) + T(Y)	-	No force is transmitted on the components. Hence only locking parameter Mech I can be realised.
2. Bolt locked through a ball 1 separate fastener consisting of 4 parts: bolt, ball, spring, ring. 	Fastening and locking: Move the fastener into the hole.	T(-Y)	Unlocking and unfastening: Push the ball into the bolt; move the bolt out of the hole.	T(ØY) + T(Y)	-	
3. Spring split pin 1 separate fastener consisting of 1 part. 	Fastening and locking: Move the fastener into the hole so that the first notch will be overridden.	T(-Y)	Unlocking and unfastening: Move the fastener out of the hole.	T(Y)	-	No force is transmitted on the components. Hence only locking parameter Mech I can be realised.
4. Cylindrical, tapered, grooved pin 1 separate fastener consisting of 1 part.  Var. 1 Var. 2 Var. 3	Fastening and locking: Move the fastener into the hole.	T(ØX)	Unlocking and unfastening: Move the fastener out of the hole.	T(ØX)	-	With the tapered or grooved pin, a locking force can be transmitted on the components resulting in Mech III locking parameter. Components can be penetrated in an angle between 60° and 90° related to the Y-axis. Examples:  
…						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B5

Generation of new locking methods



Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Fastener (sitting in the convex or concave component): Increase the length of the fastener.

Concave component (fastener sits in the convex component): Decrease the cross section dimension of the concave component hole.

Convex component (fastener sits in the concave component): Increase the cross section dimension of the convex component.

Components: Move components relatively to each other according to specific kinematics.

All, fastener and components: Move fastener relatively to the components according to specific kinematics.

Solutions for unlocking:

Fastener (sitting in the convex or concave component): Decrease the length of the fastener.

Concave component (fastener sits in the convex component): Increase the cross section dimension of the concave component hole.

Convex component (fastener sits in the concave component): Decrease the cross section dimension of the convex component.

Components: Move components relatively to each other according to specific kinematics.

All, fastener and components: Move fastener relatively to the components according to specific kinematics.

To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B6

Selection of existing locking methods

- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

Description:
The locking force is applied on the concave component and is transmitted under its elastically defomation to the convex component. Geometrical interaction does not exist and so only the locking technology Mech II can be realised.

To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Clamping hose clamp: 1 separate fastener 	Fastening: Deform fastener elastically and move it over the concave component.	ED(ØX) + T(X)	Unlocking: Deform fastener elastically.	ED(ØX)	-	Standardised, different sizes. Specific application: connection of hoses in cooling systems.
	Locking: Undo the elastically deformation of the fastener.	Undo ED(ØX)	Unfastening: Remove the fastener.	T(-X)		
2. Hose clamp with screw: 1 separate fastener consisting of 3 parts: entanglement, threaded bolt, tapped bush. 	Fastening: Move the fastener over the concave component.	T(X)	Unlocking: Rotate the screw in counter-clockwise direction.	R(-Z)	-	Locking force can be adjusted.
	Locking: Rotate the screw in clockwise direction.	R(Z)	Fastening: Remove the fastener.	T(-X)		
…						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B6

Generation of new locking methods

Legend:

- Planar or concave component to be connected
- Planar or convex component to be connected
- Fastener (Additive)
- Interface
- Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking:

Fastener: Decrease the cross section dimension of the fastener loop.

Concave component: Increase the cross section dimension of the interface with the fastener; decrease the cross section dimension of the interface with the convex component.

Convex component: Increase the cross section dimension of the interface with the concave component.

Solutions for unlocking:

Fastener: Increase the cross section dimension of the fastener loop.

Concave components: Decrease the cross section dimension of the interface with the fastener; increase the cross section diameter of the interface with the convex component.

Convex component: Decrease the cross section dimension of the interface with the concave component.

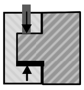
To Do:

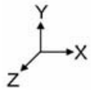
1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).

2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Connection principle B7

Selection of existing locking methods





Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

Description:
Due to the component interfaces are situated opposite to each other, locking can be realised through the transmission of forces between these interfaces. Here, the locking forces are transmitted from outside of the interfaces to the convex component through piercing the concave component. Due to no geometrical interaction exist, only the locking technology Mech II is realised.

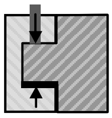
To Do:
Select from the following list suitable locking methods fulfilling the defined requirements.

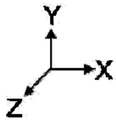
ID-number and locking method; Structure of necessary fasteners (Req. 3.3)	**Joining and locking process (Req. 3.8, 3.10, 3.12)**		**Unlocking and separating process (Req. 3.9, 3.11, 3.13)**		**Irreversible changes of components/ fasteners through locking/ unlocking (Req. 3.4, 3.5)**	**Specific properties**
	Description	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system	**Description**	**Trigger** related to the components and fasteners as positioned above and the given orhtogonal system		
1. Grub screw: 1 separate fastener consisting of one part. 	Fastening: Catch the thread of the concave component and turn the fastener in clockwise direction.	T(ØX) + R(ØX)	Unlocking: Rotate the fastener in counter-clockwise direction until the locking force is released.	R(ØX)	-	Adjustable locking force. Example: 
	Locking: Rotate the fastener in clockwise direction until the necessary locking force is achieved.	R(ØX)	Unfastening: Rotate the fastener in counter-clockwise direction; Remove the fastener.	R(ØX) + T(ØX)	-	
...						

T: Translatory movement;
R: Rotatory movement;
ED: Elastic deformation;
PD: Plastic deformation;
Ø: Movement or deformation in radial direction around a defined axis;
X; Y; Z: directions of translatory (T) and rotatory (R) movements as well as of deformations (D).

Connection principle B7

Generation of new locking methods





Planar or concave component to be connected
Planar or convex component to be connected
Fastener (Additive)
Interface
Possibility of locking force application

In the following, general solutions are listed which are enabling locking and unlocking of the connection:

Solutions for locking :

Fastener: Move the fastener relatively to the concave component according to specific kinematics.
Concave component: Decrease the cross section dimension of the interface with the convex component.
Convex component: Increase the cross section dimension of the interface with the fastener.

Solutions for unlocking :

Concave component: Increase the cross section dimension of the interface with the convex component.
Convex component: Decrease the cross section dimension of the interface with the fastener.
Fastener: Move the fastener relatively to the concave component according to specific kinematics.

To Do:

1. Generate general solutions, determining
• the area where and the directions through which locking and/or unlocking should be realised;
• the preferred kind of initiation (movement, deformation).
2. Under consideration of all components and design parameters, create specific solutions fulfilling these determinations.

Appendix D Evaluation of SYCONDE

D.1 Design task

In the following, the design task for evaluating SYCONDE as provided to the designers is given and an English translation is added.

Für die Befestigung des Waschmaschinenfrontgewichts ist eine verbesserte Verbindungstechnik auszuwählen oder zu entwickeln. Das Waschmaschinenfrontgewicht wird am Laugenbehälter befestigt (*Bild 1*). Mit der aktuellen Lösung kommt es zum Teil zu Vorspannkraftverlusten die dazu führen, dass sich das Frontgewicht bewegt und Geräusche macht. Die Verbindungstechnik soll die folgenden Anforderungen erfüllen:

- Die Form des Betongewichts soll möglichst nicht verändert werden, es sind aber solche geometrischen Änderungen möglich, die durch Materialauftrag (also Entnahme von Material aus der Gussform) oder durch das Anbringen von Bohrungen zu realisieren sind. Die Baugröße und der notwendige Bauraum sollen aber möglichst nicht verändert werden.
- Die Form des Laugenbehälters soll möglichst nicht verändert werden, es sind aber solche geometrischen Änderungen möglich, die durch Materialauftrag (also Entnahme von Material aus der Gussform) oder durch das Anbringen von Bohrungen zu realisieren sind. Beim Anbringen von Bohrungen ist darauf zu achten, dass ungewollter Flüssigkeitsaustritt aus dem Laugenbehälter vermieden wird.
- Verbinden und Verbindungslösen soll möglichst einfach zu realisieren sein.
- Mehrmaliges Lösen und Verbinden soll möglich sein.
- Verwenden möglichst weniger separater Teile um Handhaben und Verlieren von Verbindungsmitteln zu verhindern und Montage- sowie Demontagezeiten zu verringern.
- Es soll möglichst kein Vorspannkraftverlust auftreten.
- Um Geräusche durch Vibrationen zu verhindern, soll das Gewicht spielfrei mit dem Laugenbehälter verbunden werden.

Der Laugenbehälter besteht aus PP GF 30 (Polypropylen mit 30 % Glasfaser). Das Waschmaschinenfrontgewicht besteht aus Beton mit der Dichte 3,25 kg/m^3 mit einem eingelegten Stahlseil. Die Masse des Betongewichts beträgt 13 kg. Die Verbindung kann eine Neuentwicklung sein – Herstellkosten können zunächst vernachlässigt werden.

Nur EDs:	Bitte verwenden Sie SYCONDE für den Auswahl- und Gestaltungsprozess.
Nur CDs:	Bitte bearbeiten Sie die die Aufgabe wie folgt: • Entwickeln Sie so viele funktionsfähige Lösungen wie möglich. Die Lösungen sollen die Anforderungen so gut wie möglich erfüllen. • Dokumentieren Sie Ihren Lösungsweg. • Skizzieren Sie ihre endgültigen Lösungen auf den Blättern „Final solutions“. Durch die Skizzen soll das Prinzip ersichtlich sein. Beschreiben Sie kurz verbal jeweils den Füge- und Löseprozess. • Bewerten Sie Ihre Lösungen qualitativ.

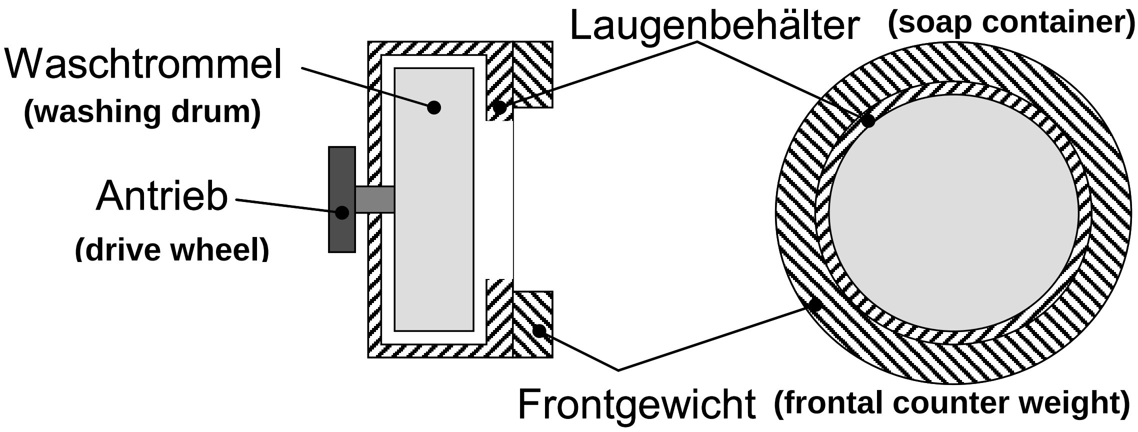


Bild 1: Schematische Darstellung des Bereiches des Waschmaschinenfrontgewichts/ schematic of the area of the frontal counter weight

English translation of the design task:

A better connection technique for the fixation of the frontal counter weight of a washing machine is to be selected or generated. The frontal counter weight is fixed with the soap container (*Bild 1*). The actual solution results to some extent in loss of preload force which causes movement of the frontal counter weight and noises. The connection technique should fulfill the following requirements:

- The shape of the weight consisting of concrete should preferably not be changed. However, changes are possible which can be realised through adding material to the counter weight (i.e. removal of material in the mold) or though adding holes. The installation size and the installation space should preferably not be changed.
- The shape of the soap container should preferably not be changed. However, geometrical changes are possible which can be realised through adding material to the soap container (i.e. removal of material in the mold) or though adding holes. If holes are added it is to be considered that an unintended outlet of water is prevented.
- Assembly and disassembly should be easy.
- Repeated assembly and disassembly should be possible.
- Preferably little separate parts should be used for preventing manual operation and the loss of fasteners, and for reducing assembly and disassembly times.
- Loss of preload should preferably not occur.
- For preventing noises, the assembly of the frontal counter weight and the soap container should be free of clearance.

The soap container consists of PP GF 30 (polypropylene with 30 % glass fibre). The frontal counter weight consists of concrete with a density of 3.25 kg/ m^3 and an inserted steel cable. The counter weight has a mass of 13 kg. The connection can be a new design – manufacturing costs are to be neglected in the first instance.

Only EDs:	Please use SYCONDE for the selection and generation process.
Only CDs:	Please solve the task as described in the following: • Develop as much functioning solutions as possible. The solutions should fulfill the requirements best possible. • Dokument your solution path. • Make sketches of the final solutions on the sheets “Final solutions“. The sketches should display the principle. Describe shortly and verbally the assembly and disassembly processes. • Evaluate your solutions concerning their quality.

D.2 Questionnaire

Figure D-1 and Figure D-2 show the questionnaires which were filled in by control designers and experimental designers after they have finished the design task. Figure D-3 and Figure D-4 contain their English translation. The numbers in the questionnaires indicate the frequency in which the defined ratings were selected.

Im Folgenden finden Sie eine Reihe von Aussagen. Bitte geben Sie für jede der Aussagen an, wie gut sie auf Sie persönlich zutrifft. Kreuzen Sie dazu auf der rechten Seite das Feld an, das Ihrer Meinung am besten entspricht.

Haben Sie einmal versehentlich ein Kreuz falsch gesetzt, so kreisen Sie dieses ein (☒) und kreuzen Sie die für Sie zutreffende Alternative an.

	Trifft voll zu	Trifft eher zu	Teils /teils	Trifft eher nicht zu	Trifft gar nicht zu
1. Mein Lösungsweg war klar strukturiert.		1	2	1	1
2. Mein Lösungsweg war eher unstrukturiert.	1	1	1	2	
3. Ich habe das Gefühl, einen großen Lösungsraum betrachtet zu haben.		1	1	3	
4. Ich habe das Gefühl, einen kleinen Lösungsraum betrachtet zu haben.		2	1	1	1
5. Ich bin mit der Qualität (auch Erfüllung der Anforderungen) der von mir gestalteten endgültigen Lösungen völlig zufrieden.		2	1	1	1
6. Ich bin mit der Qualität (auch Erfüllung der Anforderungen) der von mir gestalteten endgültigen Lösungen nicht zufrieden.	1		1	3	
7. Ich habe das Gefühl, effizient gearbeitet zu haben.			4	1	
8. Ich habe das Gefühl, ineffizient gearbeitet zu haben.		1	2	2	
9. Auch mit mehr Zeit hätte ich weder mehr, noch bessere Lösungen konstruiert.	1	1	1	1	1
10. Mit mehr Zeit hätte ich mehr und/oder bessere Lösungen konstruiert.	2	1		1	1

1. Was waren die beiden negativsten Erfahrungen während dieser Konstruktionsübung?
2. Was waren die beiden positivsten Erfahrungen während dieser Konstruktionsübung?

Figure D-1: Questionnaire for control designers

Im Folgenden finden Sie eine Reihe von Aussagen. Bitte geben Sie für jede der Aussagen an, wie gut sie auf Sie persönlich zutrifft. Kreuzen Sie dazu auf der rechten Seite das Feld an, das Ihrer Meinung am besten entspricht.

Haben Sie einmal versehentlich ein Kreuz falsch gesetzt, so kreisen Sie dieses ein (☒) und kreuzen Sie die für Sie zutreffende Alternative an.

	Trifft voll zu	Trifft eher zu	Teils /teils	Trifft eher nicht zu	Trifft gar nicht zu
1. Mein Lösungsweg war klar strukturiert.		4	1		
2. SYCONDE hat mich dabei unterstützt, meinen Lösungsweg klar zu strukturieren.	1	3	1		
3. Mein Lösungsweg war eher unstrukturiert.		1	1	2	1
4. Ich habe das Gefühl, einen großen Lösungsraum betrachtet zu haben.	2	1	2		
5. SYCONDE hat mich dabei unterstützt, einen großen Lösungsraum zu betrachten.	2	3			
6. Ich habe das Gefühl, einen kleinen Lösungsraum betrachtet zu haben.			2		3
7. Ich habe das Gefühl, dass SYCONDE mich bei der Gestaltung meiner Verbindungen unterstützt hat.	1	3	1		
8. Ich habe das Gefühl, dass SYCONDE mich bei der Gestaltung meiner Verbindungen nicht unterstützt hat.			1	1	3
9. Wenn ich das nächste Mal eine Verbindung gestalte, werde ich wieder SYCONDE verwenden.		2	1	2	
10. Wenn ich das nächste Mal eine Verbindung gestalte, werde ich SYCONDE nicht wieder verwenden.		1	1	2	1
11. Ich bin mit der Qualität (auch Erfüllung der Anforderungen) der von mir gestalteten endgültigen Lösungen völlig zufrieden.	1	1	1	2	
12. SYCONDE hat dazu beigetragen, dass ich mit der Qualität (auch Erfüllung der Anforderungen) der von mir gestalteten endgültigen Lösungen völlig zufrieden bin.		1	3	1	
13. Ich bin mit der Qualität (auch Erfüllung der Anforderungen) der von mir gestalteten endgültigen Lösungen nicht zufrieden.		2	1		2
14. Ich habe das Gefühl, effizient gearbeitet zu haben.		3		2	
15. SYCONDE hat mich dabei unterstützt, effizient zu arbeiten.		3		2	
16. Ich habe das Gefühl, ineffizient gearbeitet zu haben.		2		2	1
17. Auch mit mehr Zeit hätte ich weder mehr, noch bessere Lösungen konstruiert.	1	1	1	2	
18. Mit mehr Zeit hätte ich mehr und/oder bessere Lösungen konstruiert.		2	1	1	1

Figure D-2a: Questionnaire for experimental designers, continuation on next page

1. Was waren die beiden negativsten Erfahrungen während dieser Konstruktionsübung?
2. Was waren die beiden positivsten Erfahrungen während dieser Konstruktionsübung?
3. Was denken Sie sind die größten Nachteile von SYCONDE?
4. Was denken Sie sind die größten Vorteile von SYCONDE?
5. Was würden Sie an SYCONDE verbessern wollen?

Figure D-2b: Questionnaire for experimental designers, continuation

	fully ap-plic-able	ra-ther ap-plic-able	neut-ral	ra-ther not ap-plic-able	not ap-plic-able at all
1. My solution path was clearly structured.		**1**	**2**	**1**	**1**
2. My solution path was rather unstructured.	**1**	**1**	**1**	**2**	
3. I have the feeling I have considered a large solution space.		**1**	**1**	**3**	
4. I have the feeling I have considered a small solution space.		**2**	**1**	**1**	**1**
5. I am fully content with the quality (includes also the fulfilment of the requirements) of my final solutions.		**2**	**1**	**1**	**1**
6. I am not content with the quality (includes also the fulfilment of the requirements) of my final solutions.	**1**		**1**	**3**	
7. I have the feeling of having worked efficiently.			**4**	**1**	
8. I have the feeling of having worked inefficiently.		**1**	**2**	**2**	
9. Also with more time I would not have had designed neither more nor better solutions.	**1**	**1**	**1**	**1**	**1**
10. With more time I would have had designed more and/or better solutions.	**2**	**1**		**1**	**1**

1. Which were the two most negative experiences during working on the design task?

2. Which were the two most positive experiences during working on the design task?

Figure D-3: Questionnaire for control designers, English translation

	fully applicable	rather applicable	neutral	rather not applicable	not applicable at all
1. My solution path was clearly structured.		**4**	**1**		
2. SYCONDE supported me in clearly structuring my solution path.	**1**	**3**	**1**		
3. My solution path was rather unstructured.		**1**	**1**	**2**	**1**
4. I have the feeling I have considered a large solution space.	**2**	**1**	**2**		
5. SYCONDE supported me in considering a large solution space.	**2**	**3**			
6. I have the feeling I have considered a small solution space.			**2**		**3**
7. I have the feeling that SYCONDE supported me in designing connections.	**1**	**3**	**1**		
8. I have the feeling that SYCONDE did not support me in designing connections.			**1**	**1**	**3**
9. The next time when I will design a connection, I will use SYCONDE again.		**2**	**1**	**2**	
10. The next time when I will design a connection, I will not use SYCONDE again.		**1**	**1**	**2**	**1**
11. I am fully content with the quality (includes also the fulfilment of the requirements) of my final solutions.	**1**	**1**	**1**	**2**	
12. SYCONDE was a contribution to full satisfaction with the quality (includes also the fulfilment of requirements) of my final solutions.		**1**	**3**	**1**	
13. I am not content with the quality (includes also the fulfilment of the requirements) of my final solutions.		**2**	**1**		**2**
14. I have the feeling of having worked efficiently.		**3**		**2**	
15. SYCONDE supported me in working efficiently.		**3**		**2**	
16. I have the feeling of having worked inefficiently.		**2**		**2**	**1**
17. Also with more time I would not have had designed neither more nor better solutions.	**1**	**1**	**1**	**2**	
18. With more time I would have had designed more and/or better solutions.		**2**	**1**	**1**	**1**

Figure D-4a: Questionnaire for experimental designers, English translation, continuation on next page

1. Which were the two most negative experiences during working on the design task?
2. Which were the two most positive experiences during working on the design task?
3. What do you think are the biggest disadvantages of SYCONDE?
4. What do you think are the biggest advantages of SYCONDE?
5. What would you like to improve of SYCONDE?

Figure D-4b: Questionnaire for experimental designers, English translation, continuation

D.3 Performed activities during the design process

In Figure D-5 to Figure D-145, the performed activities as observed for each designer during working on the design task are shown in diagrams. In these, the activities are identified by numbers. Table D-1 contains the allocation of these numbers and the activities. As can be seen, all EDs performed the important activities in the order described in SYCONDE. For this reason the graphs of the occurred activities as observed for the EDs (Figures D-5 – D-9) result in patterns similar to a stair-profile. Nearly all CDs performed the activities no. 3, 6 and 7, while only few of them performed the activities no. 4 and 5. CDs (Figures D-10 – D-14) mainly jumped between the activities no. 6, 7 and 8. This resulted in patterns similar to a saw-tooth profile.

Table D-1: Allocation of activities and numbers

Important activities: **No.**	
1	Consideration of component characteristics
2	Generation of a requirements list for the connection to be designed
3	Consideration of existing locking technologies
4	Consideration of existing joining concepts
5	Generation of suitable combinations of locking technologies and joining concepts
6	Consideration of geometrical connection characteristics
7	Consideration of locking methods and application to the components to be assembled
8	Evaluation of final solutions
Further observed activities:	
9	Selection of combinations of joining concepts and locking technologies
10	Thinking/brooding
11	Reading introduction of SYCONDE/discussing about SYCONDE (only EDs)
12	Reading problem description/drawings
13	Defining connection functions
14	Looking for solutions satisfying the connection functions

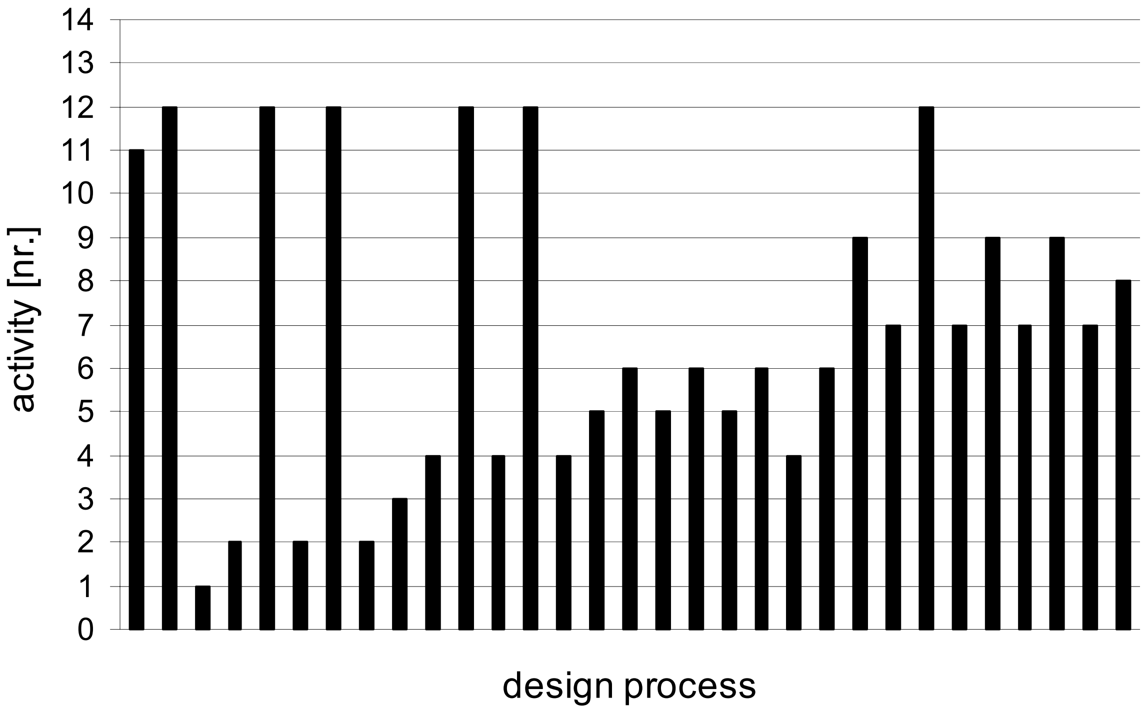


Figure D-5: Design process of ED-01

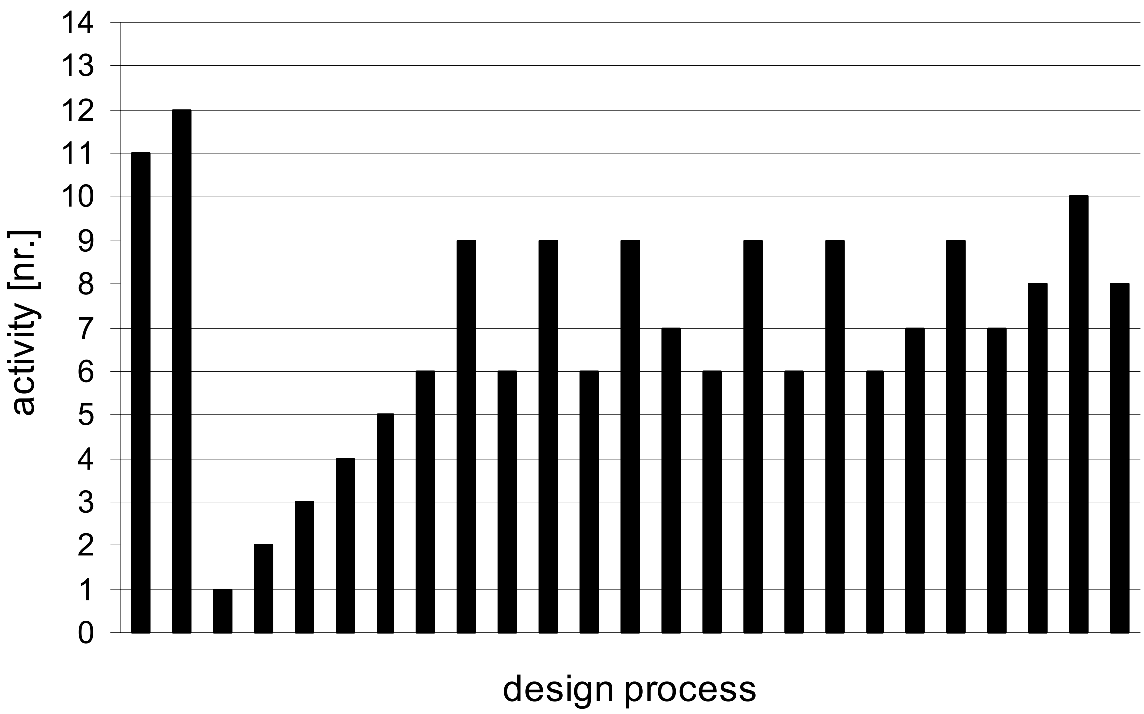


Figure D-6: Design process of ED-02

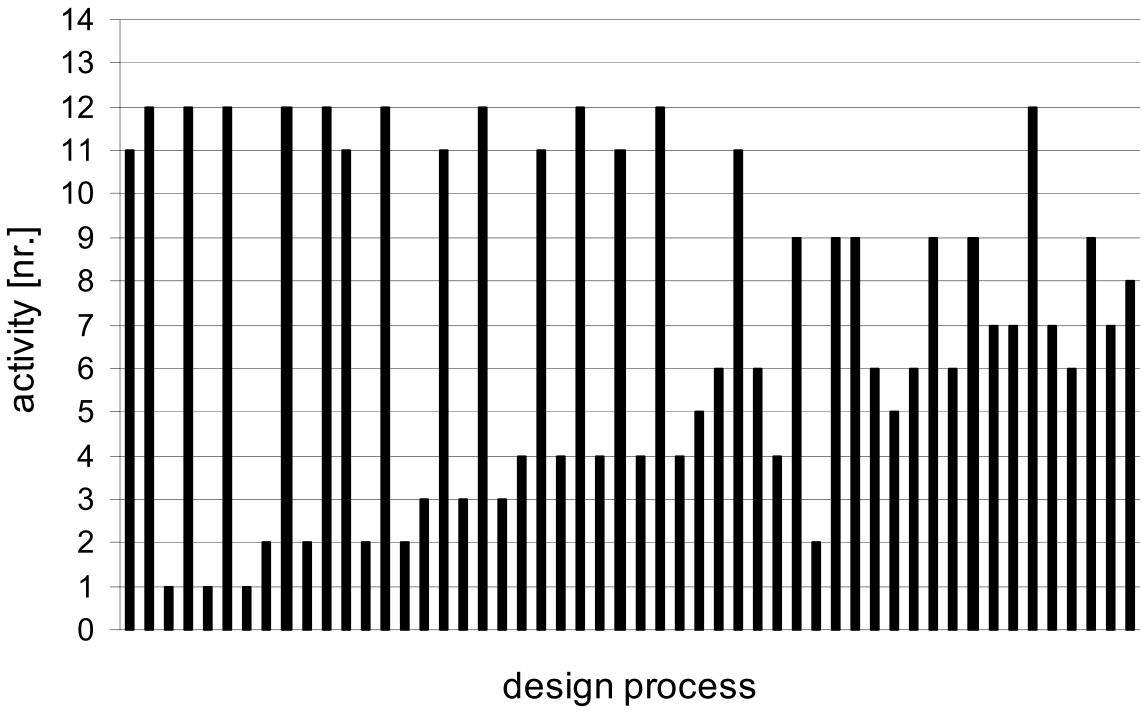


Figure D-7: Design process of ED-03

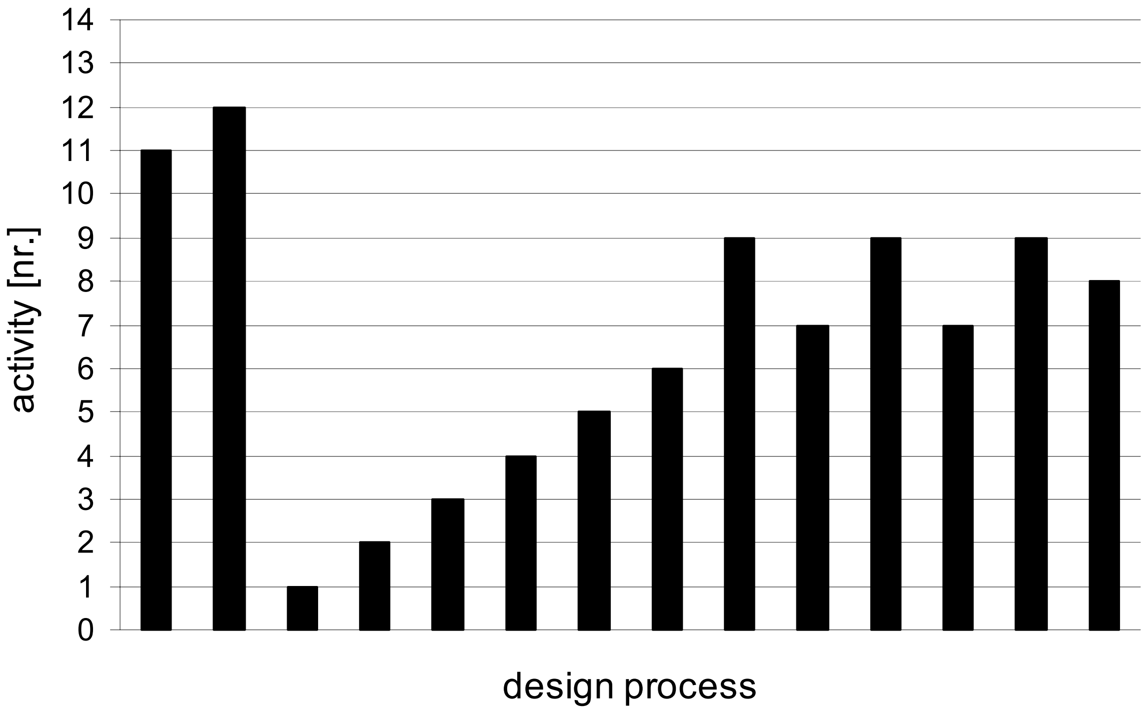


Figure D-8: Design process of ED-09

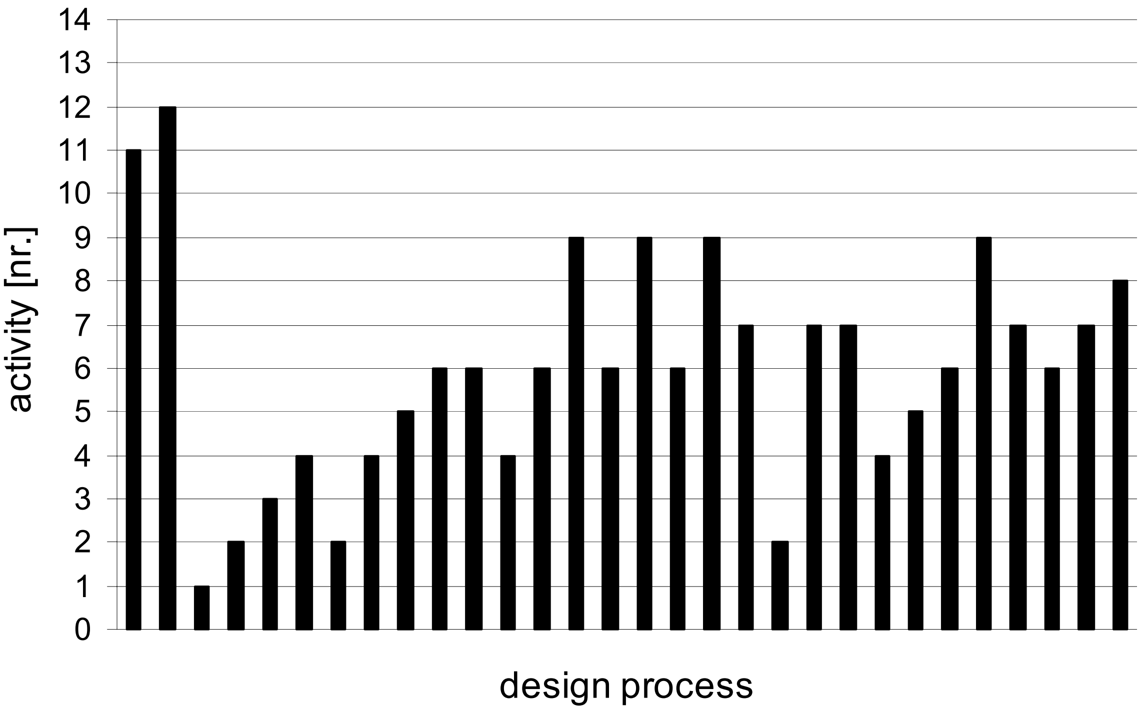


Figure D-9: Design process of ED-10

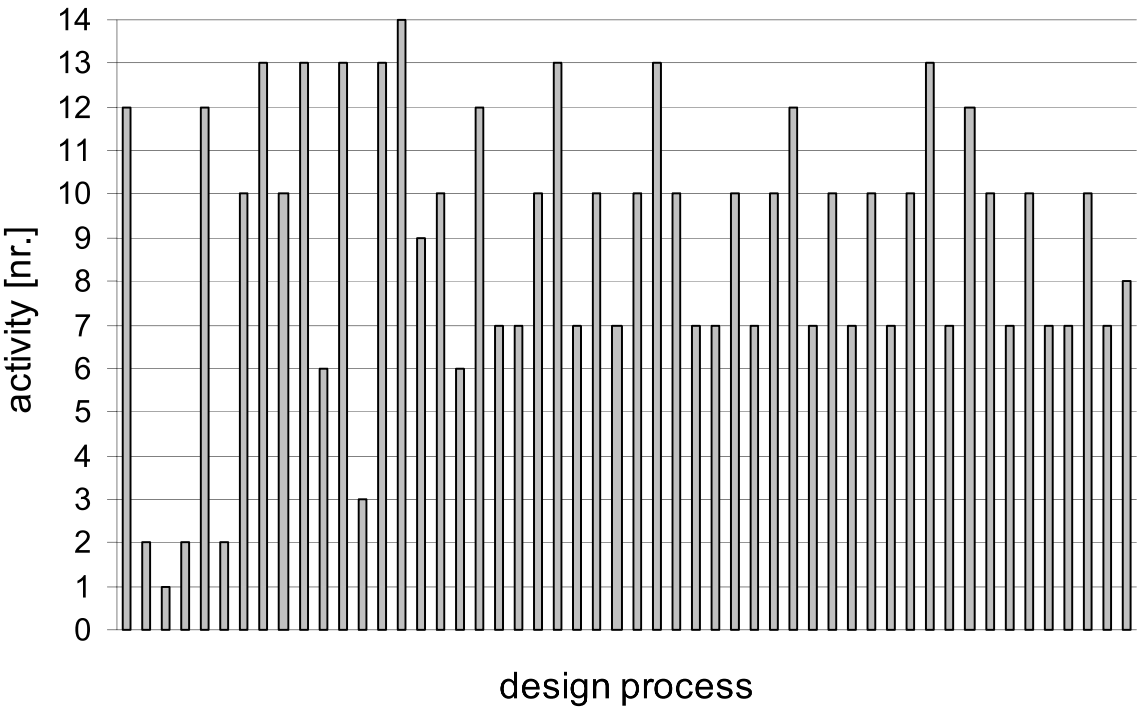


Figure D-10: Design process of CD-04

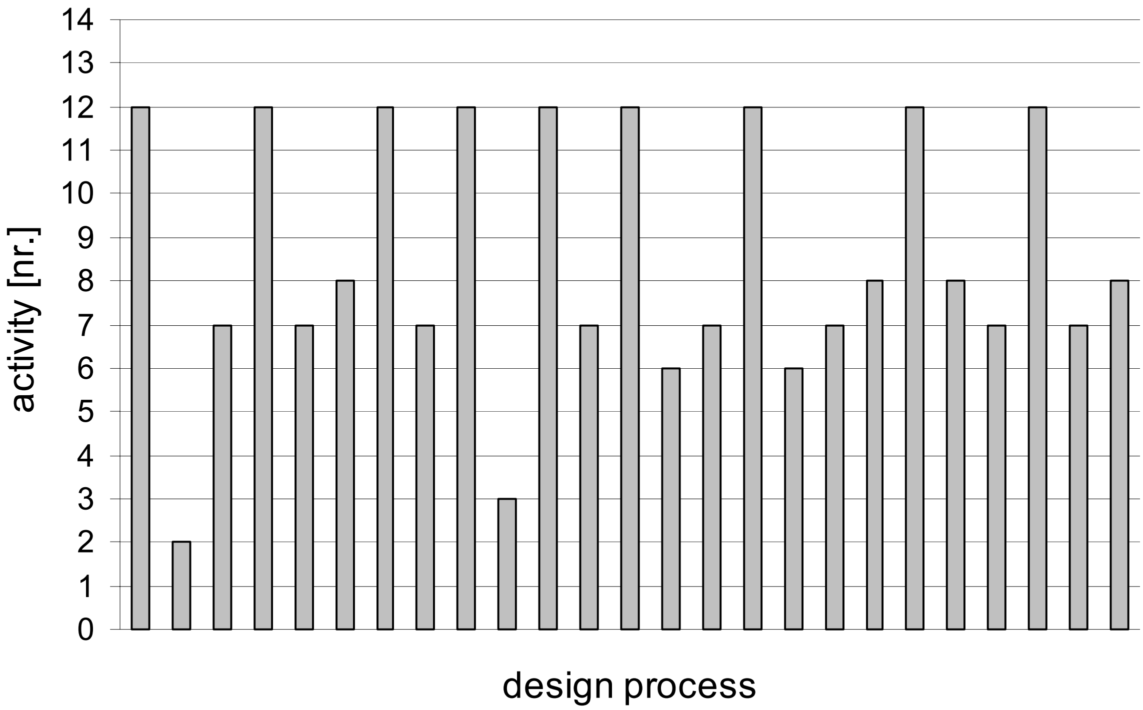


Figure D-11: Design process of CD-05

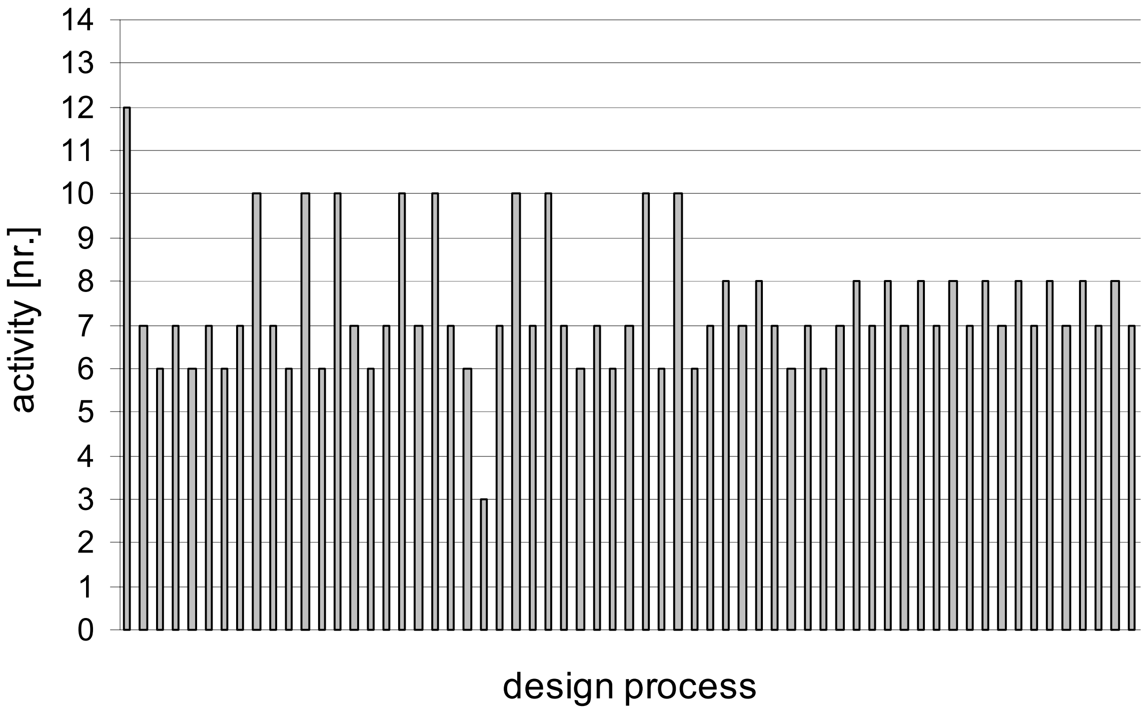


Figure D-12: Design process of CD-06

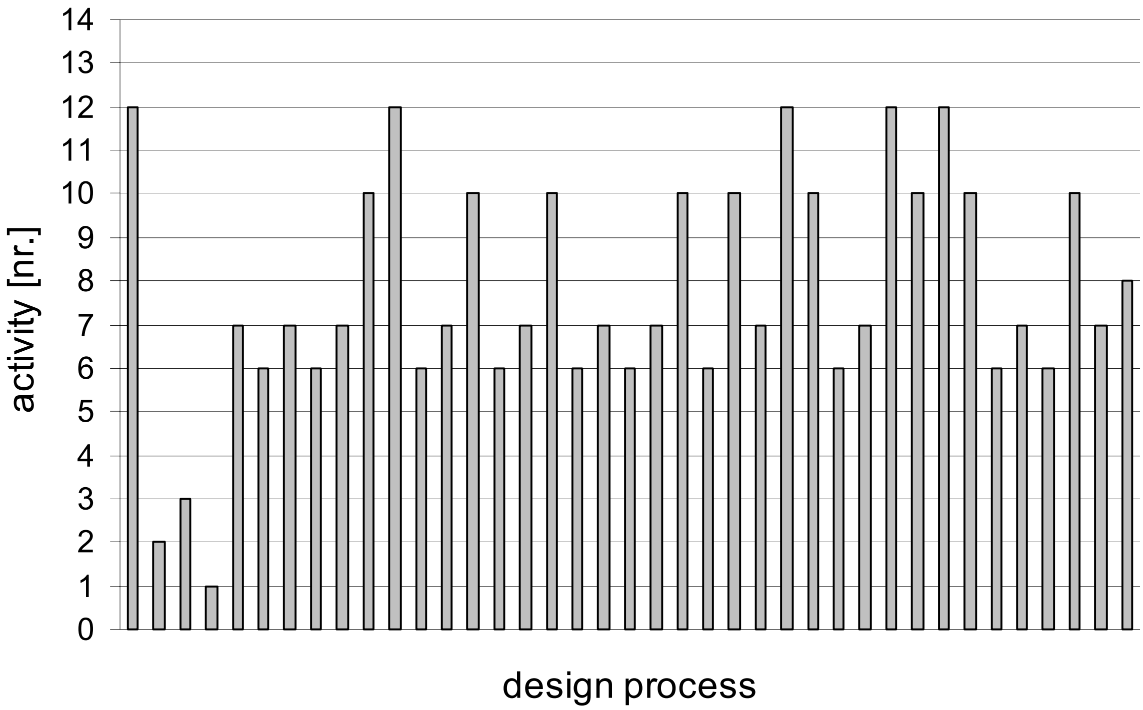


Figure D-13: Design process of CD-07

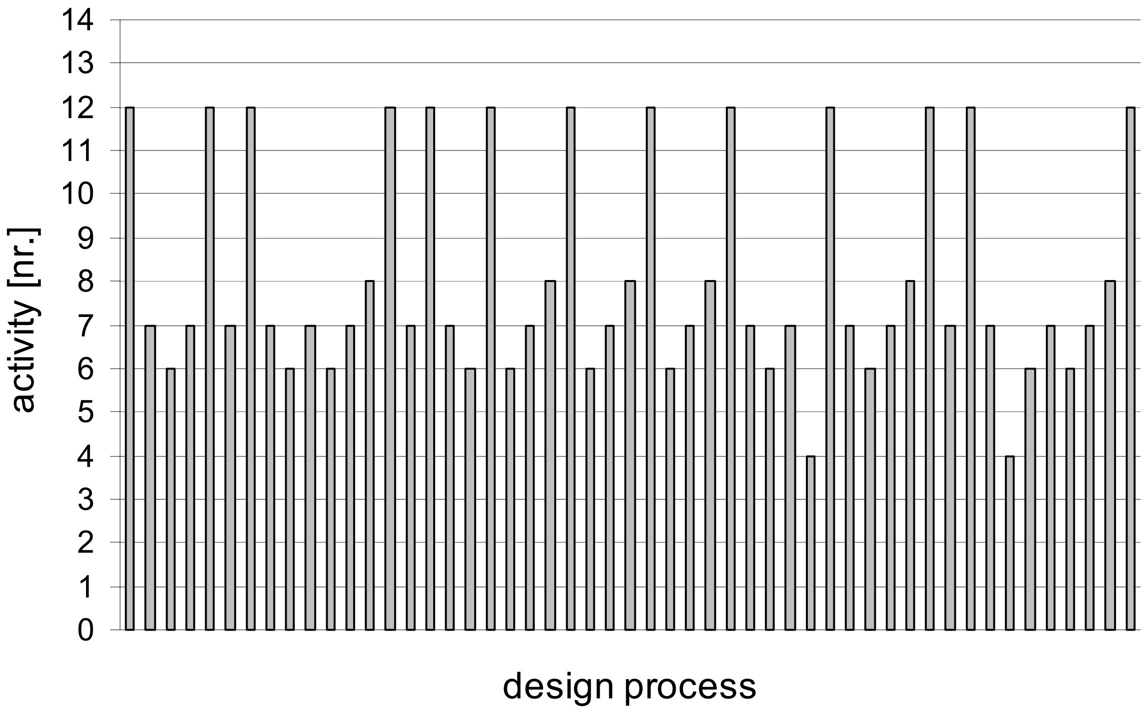


Figure D-14: Design process of CD-08

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