Development of connections in building manufacturing

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Cover: Designer evaluating a structural connection regarding assemblability using the DFA method developed in this project by Erik Jürisoo and Robert Staaf.

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Preface

Skall fullföljas tillsammans med Boverket

This report concludes the project Standardisation of connections and interfaces on building manufacturing, financed by Boverket, SBUF and NCC.

The project participants were A-betong (Göran Östergaard), Chalmers university of technology (Marie Johansson) and NCC (Dan Engström, Jonas Magnusson). Thesis workers involved were Erik Jürisoo and Robert Staaf (authors of the sections on DFA), Carl Jansson and Sven Tägtsten (authors of the sections on development methodology), Victor Lassl and Patrik Löfgren, and finally Thomas Larsson and Andreas Pamp-Magnusson. The project manager was Dan Engström.

Karlskrona, December 2007

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Appendix A: Connection Design Method

Sammanfattning

Allmänt

Byggindustrin är just nu under kraftig förändring från traditionellt platsbyggande och prefabricering till att bli mer industrialiserad. En byggsten i detta är att en stor del av produktionen flyttas inomhus till fabriker för tillverkning av komponenter som monteras samman på byggplats. För att göra denna process så effektiv som möjligt är god utformning av knutpunkter som monteras på plats av stor vikt. Dessa kommer att avgöra vilket tekniskt system som byggnaden bygger på i fråga om kraftflöden, stabilitet, akustik/vibrationer, brandsäkerhet, täthet med mera. Det är också i knutpunkterna som komponenter från olika leverantörer möts. Knutpunkterna är också av mycket stor vikt för ett rationellt montage, och kommer att avgöra vilken tid, utrustnign och metod som krävs för montaget. En sammanhållen och genomtänkt process för hur dessa knutpunkter skall utvecklas och projekteras är av mycket stor vikt. Det övergripande målet för detta projekt är att skapa metoder och och vägledning för utvecklingen av knutpunkter (särskilt för enkelt montage på plats) för industriellt byggande.

Fokus i denna rapport är därför utveckling och projektering av last-bärande knutpunkter för industriella byggsystem. Den består av tre huvudelar:

1. en metod att strukturera utvecklingsprocessen som helhet
2. en metod för utveckling av knutpunkter för enkelt montage på plats
3. en diskussion om begreppet öppenhet

Utvecklingsmetodik

Behovet av nya byggnader i kombination med ökad konkurrens och högre kvalitetskrav tvingar byggindustrin att bli mer effektiv. För att möta dessa krav har byggindustrin börjat tänka industriellt, genom att använda sig av väl genomtänkta och optimerade processer med inspiration från traditionell tillverkningsindustri. Ett bra exempel på när byggindustrin tillämpar industriellt tänkande är prefabricering av byggnadselement. För att kunna ha ett snabbt uppförande av byggnaderna måste anslutningarna hos elementen vara utvecklade för att tillåta en snabb montering.

Målet med denna del av rapoprten är att utreda hur utvecklingsprocessen för dessa anslutningar ska utföras på ett effektivt sätt. De ingående delaktiviteterna samt informationshantering ska utredas och definieras.

Utredningen har resulterat i en metod som ska hjälpa konstruktörer under utvecklingsprocessen av anslutningar. Metoden är baserad på teori från traditionell produktutveckling som används i tillverkningsindustrin. I metoden föreslås det att fyra tydligt definierade aktiviteter ska användas i utvecklingsprocessen, *Definition, Konceptuell utformning, Utvärdering och förbättring* och slutligen *Detaljerad utformning. Definitions*-aktiviteten ska klargöra strukturen för utvecklingsprocessen, bestämma hur information ska kommuniceras genom att föreslå standarddokument etc. Den *Konceptuella utformningen* ska resultera i att ett antal anslutningskoncept levereras till *Utvärdering och förbättrings*-aktiviteten där ett anslutningskoncept ska väljas och levereras till *Detaljerad utformnings*-aktiviteten. *Detaljerad utformnings-aktiviteten* ska göra anslutningskonceptet färdigt för tillverkning. En aktivitet ska avslutas med en tydlig brytpunkt där det säkerställs att målet med aktiviteten är uppfyllt. Processen ska därmed inte behöva vara iterativ mellan aktiviteterna, metoden ar uppbyggd så att godkännandet av en aktivitet är irreversibelt. Nyhetsvärdet i arbetet ligger i hög grad i att det sätter ord på aktiviteter i det intuitiva och kreativa utvecklingsskedet samt att processen är linjär och irreversibel. Metoden har bekräftats med en fallstudie där utvecklingsprocessen av ett befintligt byggsystems anslutningar simulerades.

Under fallstudien upptäcktes det att fördefinierade krav på anslutningarna i princip är omöjliga att inkludera i metoden eftersom det ska täcka alla tänkbara anslutningstyper och fall. Det är därför bättre att använda sig av icke-statiska dokument som kompletteras med krav och information under projektets gång, allteftersom information om och från systemet blir känt. Konfigurationen av de icke-statiska dokumenten ska anpassas till respektive utvecklingsprocess.

Design For Assembly

Platsbyggnation används idag i stor utsträckning inom byggindustrin men processen kan vara ineffektiv ur ett kostnads- och produktionstidsperspektiv. En industriell byggprocess kan vara en möjlig lösning. För att uppfylla kundernas krav och samtidigt hålla en låg produktionskostnad behöver byggprocessen vara flexibel. Tillverkningsindustrin har en lång tradition av industriella processer och har därigenom utvecklat flera designmetoder med mål att få en standardiserad tankeprocess. Detta examensarbete behandlar anslutningsutformning med inriktning på enkelt montage. Därför har designmetoder som behandlar detta ämne studerats för att undersöka om de kan anpassas för användning inom byggindustrin. Utöver dessa metoder har även riktlinjer från byggindustrin studerats. En uppenbar skillnad mellan tillverkningsindustrin och byggindustrin är storleken på produkter och delar. Hela montaget tenderar att vara större inom byggindustrin. Dessutom utförs produktionen i tillverkningsindustrin i en väl anpassad miljö vilket är ovanligt i byggindustrin.

Studien resulterade bland annat i krav som visar att en designmetod ska vara komplett, systematisk, mätbar och användarvänlig. En designmetod för kraftöverförande anslutningar i industriellt byggande har utvecklats med utgångspunkt från studien. Metoden är uppdelad i fyra steg och börjar med riktlinjer för utformning av anslutningar som är enkla att montera. Anslutningsförslagen som ska utvärderas med hjälp av metoden måste förklaras med figurer och text. För att säkerställa att anslutningen exempelvis klarar att ta upp dimensionerande last kontrolleras absoluta krav med en checklista. Nästa steg i metoden är en utvärdering av anslutningarnas montagevänlighet. Utvärderingen är baserad på kriterier som är uppdelade i tre påståenden. Ett betyg sätts på varje kriterium beroende både på anslutningens egenskaper och på kriteriets relevans. Resultat av utvärderingen är ett medelbetyg samt ett montageindex för varje anslutning. Utvärderingsmetoden har förbättrats och säkerställts med hjälp av en fallstudie. Slutligen minimeras antalet delar genom en frågeprocedur. Design med metoden bör ske iterativt.

Det är viktigt att poängtera att montaget är en av flera aspekter som måste tas hänsyn till i en designprocess. Denna del av rapporten fokuserar dock på montaget eftersom det har stor betydelse för byggprocessen.

Öppenhet

De flesta byggsystem kan definieras som öppet (eller slutet) genom att man väljer att diskutera öppenhet exempelvis ur ett visst perspektiv, en viss tidsaspekt eller en viss komplexitetsnivå. Vi bör diskutera öppenhet som det multifacetterade begrepp det är. Vi bör inte söka öppenhet i *produkter* utan i de *processer* vi använder. Dessa processer och principer utvecklas med ökande industriell mognadsgrad i byggsektorn. De blir viktiga verktyg för att byggsektorn skall kunna utnyttja flytten av tillverkning från bygglpats till fabrik. Med en sådan definition av öppenhet bibehålls affärsmässiga incitament att utveckla system, för varierande arkitektur, för introduktion av nya företag i värdekedjan. Onyanserade uttalanden om huruvida system är öppna eller slutna blir då semantiska övningar.

I detta kapitel ges ett förslag för hur olika aspekter på öppenhet kan definieras och hanteras. Den mest intressanta slutsatsen från detta resonemang är att *öppenhet i värdekedjan och i varierad arkitektur inte är kompatibla mål*. Om vi söker öppenhet både i värdekedjan och i varierad arkitektur behöver vi många olika system med olika målgrupper. Målet med detta kapitel är att inbjuda till en diskussion kring dessa frågor i allmänhet och denna slutsats i synnerhet.

Summary

General

The building industry is at moment transforming from the traditional building on site to become more industrialised. The process aimed for can be called building manufacturing. A building-block of building manufacturing is that a large part of the production is moved indoors to factories for manufacturing of elements that will be assembled on the construction site. In order to make this process as effective as possible the connections between the elements assembled on site is of utmost importance. These will to a large extent decide the technical system of the building, in terms of load paths, stability, acoustics/vibration, fire safety and air tightness. These are also the points were elements from different suppliers will meet. The connections between the elements are also significant for a rational assembly and will decide the necessary time and equipment necessary for assembly. A united and thorough process how to design these connections is incredibly important. The overall aim of this project is to create methods and guidelines for the development of connections for building manufacturing (particularly for easy assembly of elements on construction/assembly sites).

Thus, the focal point of this report is the development and design of load-bearing connections for building manufacturing systems. It consists of three main parts:

1. a method to structure the development process as a whole
2. a method for design of connections for easy assembly on site
3. a discussion of the concept of openness

Development methodology

The need for new buildings in combination with higher competition and quality requirements forces the building industry to be more effective. In order to achieve this, the building industry has started to think industrially, by using well-planned and optimised processes with inspiration from

traditional manufacturing industry. Prefabrication action is a good example of when building industry is utilizing industrial thinking. Prefabrication involves manufacturing of elements in factory and assembly on-site. In order to achieve effective erection of the houses, the structural connections must be developed to allow easy assembly.

The aim of this section is to investigate how the development process of structural connections should be structured, including activities as well as how and which information that should be communicated during the process.

The investigation resulted in a method that should aid designers during the development process of connections. The connection development method utilises ideas from traditional product development, used in the manufacturing industry. The method suggests four clearly defined activities that should be included in a connection development process, *Definition, Conceptual design, Evaluation and improvements* and finally *Detailed design*. The *Definition* activity should give the structure of the development process, stating how information should be treated by suggesting standard document formats, etc. The *Conceptual design* activity should result in a few connection concepts that should be evaluated in the *Evaluation and improvement* activity, which should deliver one connection concept to the *Detailed design* activity. The *Detailed design* should make the connection ready for manufacturing. The activities should be iterative. However, the process is intentionally not iterative between the activities – the activities end with a clearly articulated breakpoint. The activity’s aim should be confirmed before the next activity is initiated. To a high degree, the new knowledge in this work consist of that the intuitive and creative activities are explicitly defined. The method was confirmed with help of a case study. The development process of an existing building system’s connections where simulated in the case study.

In the case study, it is concluded that predefined requirements and demands on the connections are more or less impossible to include in the method, due to the fact that there exists so many different types and situations. It is therefore better to use non-static documents that should be completed during the development process as new information about the system is known. The set up of the document should be adjusted for each development process.

Design For Assembly

Today, on-site production is a common construction technique in building industry, which can be inefficient regarding cost and production time. Therefore an industrial construction process is needed. Building industry should both be flexible in order to meat the users’ demands and at the same time keep a low production cost. Knowledge could be gained from manufacturing industry which, during a long tradition of industrial processes, has developed several design methods in order to standardise the way of thinking. This section addresses connection design with focus on assembly, therefore methods concerning assembly were studied in order to see if they could be adjusted and used in building industry. In addition to the methods, guidelines from building industry were investigated. An obvious difference between manufacturing industry and building industry is the size of products and parts; the whole assembly will be larger in building industry. Production in manufacturing industry is also performed in a suited location, which is unusual for building construction.

During the study, different demands on design methods were found; a design method should for instance be complete, systematic, measurable and user-friendly. With the knowledge from the studies, a four step iterative design method for structural connections in industrial construction was developed. The method starts with guidelines aimed to help the designer develop connections which are easy to assemble. Next, design proposals, which should be investigated with help of the method, have to be described with comments and figures. Then absolute demands, depending on the design situation, are controlled using a checklist. A connection must for example withstand design loads. The next step is an evaluation regarding the connections' assemblability, consisting of criteria divided into three statements. A grade is calculated for each criterion depending on the studied connection's performance and the criterion's importance. The result of the evaluation is a mean grade and an assembly index for each connection. A case study has been performed in order to improve the method and it has shown that the evaluation method works satisfactory. The last step of the method concerns reduction of unnecessary parts. When using the design method an iterative procedure is recommended.

It is important to stress that assemblability is one aspect among many which have to be considered during a design process. However, assembly has a major impact on the total production process and was therefore chosen to be the focus in this project.

Openness

Any system can be defined as open (or closed) only by a decision to discuss openness for a certain recipient, from a certain viewpoint, a certain time-frame and a certain level of openness. We should talk about openness as the multifaceted concept it inherently is, and we should not seek it in the *products* we produce but in the *principles* that we use. These principles will develop with increasing industrial maturity in the construction sector. They will become important tools for the sector to be able to utilise that we move manufacturing into the factory. With such a definition of openness, the business incentives remain for developing systems, varied design, and for new companies to be introduced into the value-chain and so on. Unilateral categorisations whether or not different systems are open become semantic exercises.

In this chapter, a suggestion is given for how to define the different perspectives of openness in different systems. The most interesting conclusion is that *openness in the value-chain and in individual designs are not compatible goals*. If we want openness in both the value-chain and in individual designs, we need many different systems, catering for different market segments. The aim of this chapter is to invite to a discussion on this subject in general and this conclusion in particular.

Introduction

Industrial Context

Traditionally, buildings in Europe have been constructed manually on-site and engineered for one project at the time. In comparison to other industries, where many prototypes are built and tested before the final product is completed, the building industry has always been building one prototype, which also serves as the final product. This means that any problems with the building have to be corrected either during production or, in worst case, while it is in use. This can be both costly and produce a poor performance of the final product. However, this way of manufacturing also gives one big advantage; namely the freedom to construct buildings in any shape and form after the clients requirements.

The building sector is probably the only industrial sector that has not seen any major effectivisation during 20th century, the production processes has not been significantly developed since 1960. The number of working hours has instead increased due to new requirements on product quality. This method can be justified when it comes to repair and reconstruction, but not in the construction of new structures. Another growing problem is the lack of skilled construction workers in Europe (Brege et al. 2004). By changing the construction industry to a more industrialised industry several of the problems mentioned above will be overcome.

An open building system is difficult to define. The definition used in this paper is a system that provides individual user-oriented designs with an increased flexibility, compatibility and interchangability of components and alternative assemblies with standardised connections that allows for future changes without costly measures. With an industrialised open building system it should be possible to reduce the building costs and time while at the same time produce buildings of high quality according to the requirements of the customer. To achieve this, it is important to have a well working product development stage where the components are designed and a project development stage where the actual building is designed from the pre-defined products. In this paper building components are defined as the parts that are assembled on site to create a building, i.e. a wall component, connection detail etc.

One very important factor to create an effective building process is to make the assembly on the construction site more efficient. For a one-family house the costs at the construction site is about 25% of the total building cost. By using a more effective process it is possible to cut this cost by 50% (Brege et al. 2004). In order to do this, the assembly time at the building site must be reduced. The most critical part to make the assembly faster is the connections between the building components. The reason why the design procedure for connection details is interesting to study is that open industrialised construction sets new requirements on the connections, compared to traditional construction. These requirements derive both from the demands of faster assembly and from the fact that highly refined components from different manufacturers are to be used and connected to each other.

Problem

The project started out as a typical engineering research project on connections between different building components, formulating and addressing problems that have a technical solution. The more the work developed, the more we realized that the way to address connections in building manufacturing is not to approach them on a technical level, but on a methodology level – we should deal with how we *work* with connections, not what their final *designs* happen to be.

In the creation of a connection several partners are usually involved; the system owner (the company that is responsible and owner of the system at hand), the producers of the building components, the producer of the connection detail, the production partner responsible for the assembly. The statical building system is to a large extent dependent on the connections. To find a way to communicate all requirements set on a connection detail is therefore very important to achieve a rational building process.

Connections in building manufacturing systems

In contemporary industrial manufacturing, most joints are no longer connected at the final assembly. In the early days of factories, material was brought to the factory floor where it was made into components and assembled, and surfaces were finalised late in the process. This involved a great many connections, often one per function. Given that final assembly is a cost-driver, the logical step to take was to move away from keeping all processes under one roof and outsourcing sub-assemblies, not only components. This had the added benefit that the quality of the subassembly could be managed and controlled at the subassembly plant, where they are experts at producing this specific sub-assembly. Contemporary industrial production thus involves subassemblies being made off-site and very few connections in the final assembly.

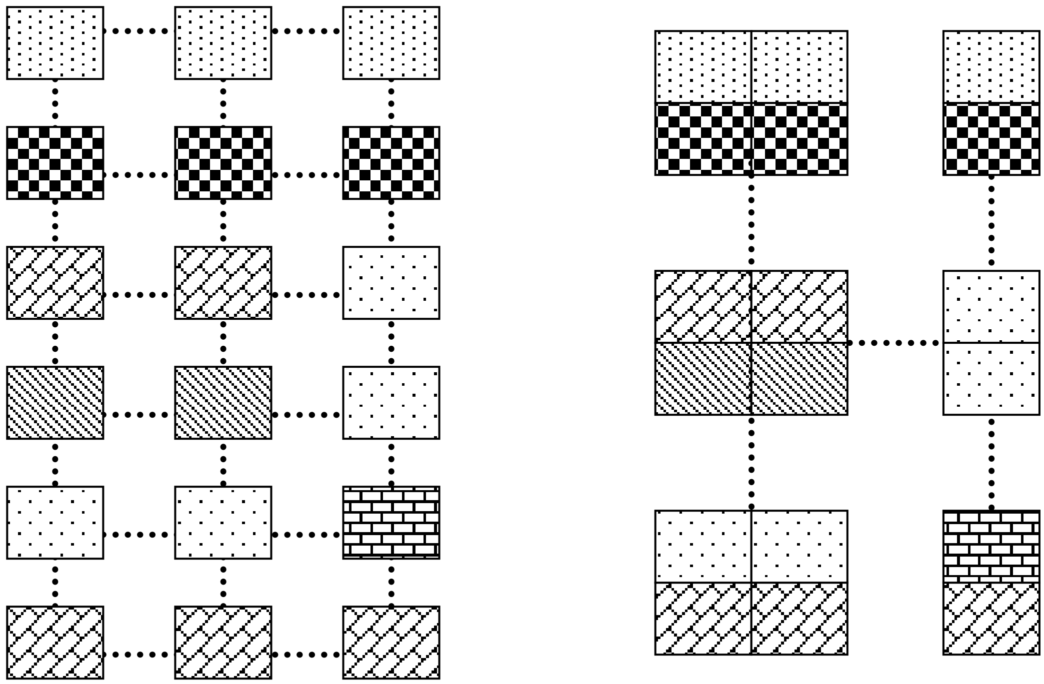


Figure 1 *Traditional construction: 27 joints at final assembly* *Building manufacturing 5 joints with components assembly*

The simple schematic example in Figure 1 illustrates the significant change in the approach to connections. By thinking "outsourced sub-assemblies" instead of "site-assembly of materials and components", it is possible to reduce twenty-seven site-joints to five. These five joints need to perform all functions that the twenty-seven joints performed.

This is not new to construction. In prefabricated construction, these concepts have been dealt with for decades. The new feature in construction is that the sub-assemblies to great extent have finishes attached in the factory. The connections cannot depend on any work on site that involves the risk of damaging the wall-paper. In addition, in order for all parts to fit and connect without the need for site-adjustment, wet trades and so on, tolerances need to be on par with the manufacturing industry. The practical upshot of this is a new role for connections in construction. Development of connections needs to be structured and communicated accordingly.

The conclusion from a survey undertaken in this project by Larsson and Pamp-Magnusson (2007) is that most people in the building sector today do not regard the traditional methods of communicating as a problem. The common opinion appears to be that mistakes that are made in design often are identified before they have a major effect on the construction site. But if we are to succeed in increasing quality and lowering costs through building manufacturing, there must be little acceptance for this sort of solve-it-later attitude. Mistakes will be made, but my mistakes must be kept on my drawing board. Improvements should found by discussing what is on the drawing board with the other actors in the value.chain. There is the need for a design process which includes issues related to purchase, logistics, production, assembly and so on.

The survey indicates a positive view of the possibilities to standardise design and communication of connections to a limited extent. This would be a way of opening the construction sector and simplify the collaboration between stake-holders. However, the readiness to abandon ones own connections varies between the suppliers included in the survey. It would appear as though it is relatively easy to embrace the new methods, as long as one does not have to abandon the old ones. This report aims to facilitate the introduction of building manufacturing concepts in connection development.

Aims and method

General

The original aims of this project were:

- create a strategy for standardisation of requirements on connections in open systems for good, sustainable building manufacturing homes,
- identify concrete development needs for connections,
- identify possibilities in other industrial sectors,
- identify new uses for existing connection types.

Overall, these aims are addressed and fulfilled in this report. The only aim that is not addressed is the aim to identify new uses for existing connection types. The reason is that the aims were written without the key knowledge gained in this project, which is this: in building manufacturing (indeed in all industrial processes) technical solutions are only interesting as building-blocks in a developed process. There is not really such a concept as stand-alone technological development for an industrial process, because industrial processes are all about knowing the constribution of each activity to the greater whole. The project therefore evolved over the course of time from a technically focused project into into addressing the methods and processes in which technology is developed. For example, the project addresses connections of prefabricated elements, but the main focus of the development methods is not prefabrication per se but the industrial thinking used to make the best use of prefabrication.

This project addresses structural connection design only, but the methods developed can be adapted to other design situations in building industry. The design concerns the product development stage, i.e. the development of a building system, and not the development of a specific project where the system is adjusted to meet certain demands.

The methods developed aims to cover all the requirements necessary for connections such as: technical specifications, information handling, tolerances and assembly. The work comprises of interviews, theoretical calculations of requirement levels and case studies to validate the created methods and guidelines.

Development methodology

In order to achieve a rational open building system without limiting the possibilities for construction of varying architecture and design, industrial thinking should be applied in the development processes. Today, this is not a regular feature in the construction industry.

This section of the report aims to develop a method for development of connections in an industrial building system.

In order to develop a structured method for connection design the development process is divided into sub-activities. These sub-activities are then studied in detail. The studies include information exchange; during the development process, within and between the activities and between the system development and the connection development. All of these investigations should result in a method, which can aid the product development team during the development of connections. Supported by this the method a development process can be more rational, effective and reviewable. It should also support the product development group to plan the process from the very beginning. An industrial development process should also secure the quality of the product.

Design For Assembly

In order to pave the way for industrial efficiency in the building industry, this section aims to suggest a method of how to design and evaluate structural connections in building structures which makes elements easier to assemble. The aim can be divided into two parts as follows below.

Firstly, the aim is to analyze design methods used in manufacturing industry. These methods should be studied in order to find out if they are applicable in building industry or difficult to use. If possible, potential needs for improvement should be identified and described. Also guidelines from building industry should be examined in order to adopt useful information.

Secondly, the aim is to adopt the studied techniques and methods used in manufacturing industry and adjust them to a design and evaluation method for structural connections in industrial construction. When the method is developed, the special needs of building industry should be considered. The final method should consider development and evaluation of structural connections. When using the method, studied connections should be compared and possible areas for improvement should be identified.

In order to make the content more clear, the aim described above can be presented in two short notations:

- Investigate potential design methods in manufacturing industry and guidelines used in building industry. Identify their need for improvement in order to match connection design in industrial construction.

- Develop a design and evaluation method for structural connections in industrial construction, including case study verification.

In order to achieve these aims and get a theoretical knowledge of the subject, literature studies were performed. Moreover, visits were made at building sites and at a production line at a car manufacturer in order to get more understanding of the present situation in building industry and manufacturing industry. The theoretical knowledge, gained in the studies, was then used to develop a design method for connections used in building industry with focus on assembly. The design method was checked, calibrated and improved with help of a case study.

The method focuses on assembly on site where most of the economical savings can be made; assemblies that are performed in a factory are not considered.

The work gien in this section is partly based on Lassl and Löfgren (2006); *Smart connection development for industrial construction*.

Openness

The final section of this report invites the reader to a discussion on the concept of openness. The aim is to question current attitudes towards openness and to begin to link openness to the end-results of building manufacturing. As discussed brifely above, we should talk about openness as the multifaceted concept it inherently is, and we should not seek it in the *products* we produce but in the *principles* that we use.

Structural Connections

The chapter begins with a definition of structural connections, followed by a presentation of demands that the connections must fulfil, generally taken from Betongvaruindustrin (2005).

Definition of Structural Connections

In order to develop a method for connection design and evaluation, it is necessary to define the connections. They can be defined in many different ways. It could for instance be defined as just a dowel, connecting two elements. However, in this project a structural connection is defined as the zone where two or more parts of a building meet, attach and join. A connection includes the influenced parts of the elements to be assembled, for example the part of a concrete element that is influenced by the reaction forces from a concentrated bearing. This definition is chosen in order to see the connections in an overall context.

Demands on Structural Connections

When designing a structural connection it is important to consider several demands. Industrial construction results in new demands on the building process since each building then consists of several prefabricated elements. All elements should be tied together using structural connections instead of being constructed as a single unit, see Figure 2.

Even though this project focus on methods for easy assembly, it is important to point out some other demands that need to be considered when designing a connection. Demands regarding the whole building structure can often be transformed to demands concerning the connections. The demands have in this project been divided into three categories; load-bearing capacity, serviceability and sustainability. However, this section starts discussing structural behaviour in general.

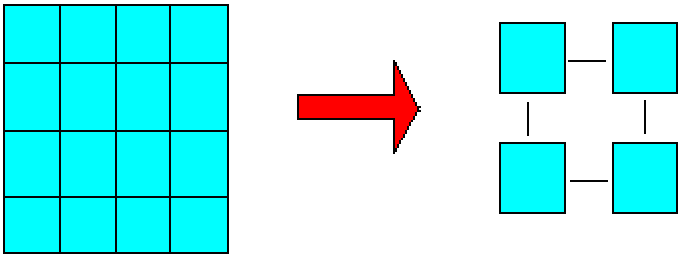


Figure 2 In industrial construction, buildings consist of prefabricated elements that has to be tied together using structural connections.

Structural Behaviour

Different actions that will give rise to loads or in other ways affect the structure during its service life are important to identify. The following text will therefore discuss some of these actions.

When a connection is designed, it is necessary to decide which loads that should be transferred and which forces that may arise in the connection. It has to be decided how alternative connection designs withstand these actions. Forces and movements are a result of for example imposed loads, loads from snow, wind, creep, shrinkage, temperature changes, variations in relative humidity, and settlement. All these influences affect the need for strength and movements in connections. A frame work, for example, and its connections, must either have some ability to move or to be able to resist restraint forces that will appear. If not, the connections or the element will be damaged or, in worse case, fail.

Connections and elements should have an ability to move and deform, as discussed above. Connections must, however, be designed to keep the deflections at an acceptable level in the service state. Deflection mainly depends on the stiffness of the elements, but in some cases deflection has to be considered in the connection design. Deflection is often not decisive for failure; it is then limited by the users' opinion of which level of deflection that is acceptable. Also the thermal elongation of members has to be considered, as this result in restraint forces and/or need for movement. For this reason, connections should for example be able to resist or be protected against fire without loss of strength. This can be extra important for some materials, e.g. steel, which can easily be weakened by fire.

A connection can be able to both deform to some extent and at the same time resist some restraint forces, as the connections can be designed to be partly restrained. In this case the connection deforms when load is applied, so that the restraint forces decrease. As an example a connection that is designed to be simply supported can, under certain circumstances, function as partly fixed. This is the case when a floor element is placed between the upper and the lower wall. Before the upper wall is connected, the floor element will be simply supported, but as soon as the wall is in place there might be a bending moment due to the fixation. Due to this moment, there might be unintended tensile stresses in the top of the floor element. The behaviour can thus be different for assembly, normal use, extreme loads and long term loading.

Additionally, all connections should have a ductile behaviour, i.e. be able to have large plastic deformations before failure. This is important to consider for example for a system of columns. Even if a column is damaged the floor above should not collapse. The connections have to withstand the loads despite large deformations and they should not have a brittle behaviour.

Load-Bearing Capacity

The most obvious demand is the load bearing capacity, i.e. the connection has to be able to transfer the design actions. There may be different types of load at different stages, i.e. during construction, during the service life and at possible accidents. A connection has to resist the design loads at all stages. Even if an element fails, its connections must be strong enough to hold the rest of the elements together preventing a progressive collapse. The loads acting on a connection at collapse can accordingly be completely different from the loads in the ordinary design situation. There can be several types of forces affecting a connection. It should be able to withstand tension, compression, shear or bending moment, or a combination of two or more of these forces. Each will be presented below.

Compressive force: The most common way to transfer compressive forces between elements is by simply placing one element on top of another. It is important that the compression stresses are spread evenly over an area, else concentrated forces will arise. It is also important to investigate the effect of local compressive forces under concentrated loads. This is extra important regarding timber structures where compressive forces perpendicular to the grain can be dangerous due to the low strength in this direction, and for concrete structures where splitting effects may cause cracking.

Tensile force: Regarding tensile force capacity, there is a large difference between different building materials. Concrete does, for example, not have very high tensile strength, and it is therefore important that the tensile force is transferred through the connections to the reinforcement in the members. The reinforcement bars also have to be anchored properly. The anchorage capacity depends on the surface of the bar, the strength of the concrete and the anchorage length. As steel bars usually are used as reinforcement in concrete structures, it is understandable that steel has a high tensile capacity. Another beneficial property of steel is that the tensile capacity is equal in all directions. This is not the case for wood based materials, as timber beams, where the tensile capacity can differ depending on if the load is applied perpendicular or parallel to the grain.

Shear force: In some cases, e.g. in concrete structures, friction between elements or connection details can be used to resist shear. With rough surfaces there will naturally be a shear resistance if there is a compressive force or reinforcement perpendicular to the surface preventing the surfaces from moving apart, see Figure 3. If a dowel is used to resist shear, splitting has to be considered. The dowels should not be placed too close to a free edge. Possible splitting patterns can be seen in Figure **Fel! Hittar inte referenskälla.**. In industrial construction, it is important to be able to transfer shear forces between elements and from elements to the foundation, illustrated in Figure 0.1. This sets extra demands on the connections which might need to transfer the force through small areas.

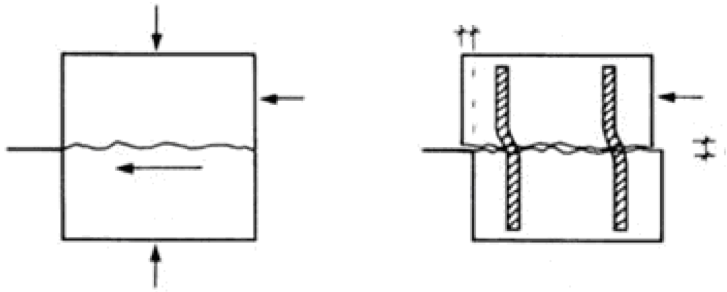


Figure 3 Friction can resist shear when compression is applied perpendicular to the surfaces or when the pullout resistance of pullout tie bars is activated by the shear displacement, from Betongelement-föreningen (2000).

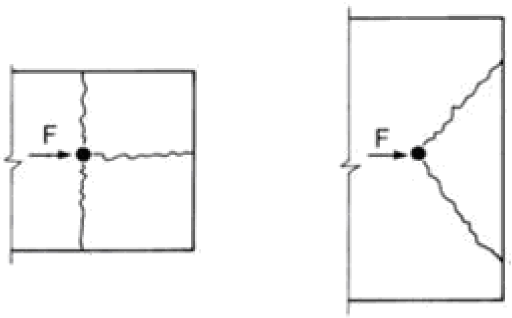


Figure 4 Possible splitting modes for a dowel close to a free concrete edge, from Betongelementföreningen (2000).

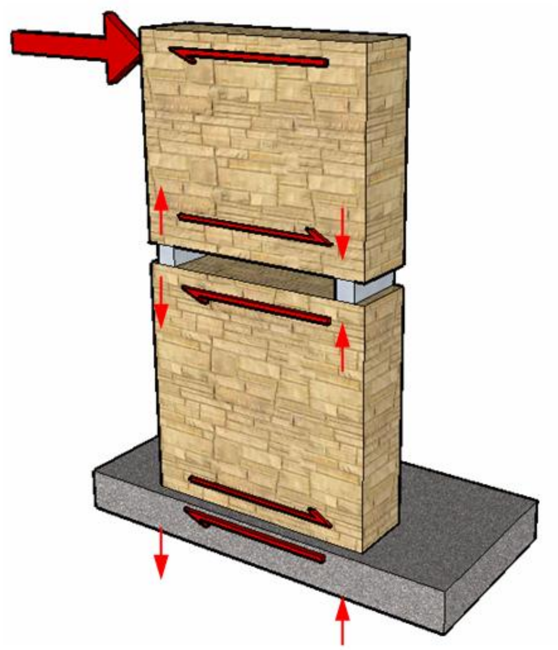


Figure 0.1 Forces between elements.

Bending moment: Moment resisting connections can be used to stabilise elements and buildings. The requirements on such connections are often harder and the connections can be more complex. One way to make a moment resisting connection less complex is to use interaction between two or more force transfer mechanisms, since bending can be a combination of tensile and compressive forces both effects has to be considered in design.

Serviceability

The connections must function satisfactory during its service life and have acceptable appearance. Some aspects pertaining to this are discussed below.

Appearance

The appearance of a building or connection is hard to grade since there exist no definitive guidelines regarding this subject. The opinion of beauty is individual and depends on the observers' point of view, culture and fashion. It is also important to note that the observers can change their definition of beauty over time and therefore even their opinion of appearance. Appearance can be called a soft requirement, which is difficult to quantify.

Visible connection details are often undesired; they are preferred to be hidden. The user, of for example an apartment, should not have to see connection details between building elements. If a connection detail on the other hand is visible, it can be designed to either be a part of the architecture or blend into the structure, according to *fib* (2007). If engineers and architects cooperate, a building structure can be formed as an aesthetic expression. This is called tectonic architecture which is important also for connection design. Aesthetic design and its technical and structural consequences are not treated further in this project but are discussed by Engström *et al.* (2004).

Building Performance

Connections have to be tight for many reasons, e.g. transport of water, moisture and air. These transports must be prevented to avoid damages of the building and problems with indoor climate. Leakage can be a problem regarding ventilation; the ventilation system might be disturbed and malfunction if the building is not tight enough. Heat can also be transported through sections that are not sufficiently tight. It is also important to consider the risk of thermal bridges and the connections need to be designed to avoid these. This can be a problem in an energy point of view, as major heat leakage can result in unnecessarily large energy consumption. Furthermore, sound and vibration can give an unpleasant environment for the users of a building. The disturbance often comes from the surrounding environment as traffic or neighbours. The connection, that often is the decisive part of the structural system, has to be designed tight in order to ensure the building environment with regard to sound and vibration.

Tolerances

One of the most difficult issues in industrial construction concerns tolerances. Naturally, the elements to be assembled, and their connections, have to be designed with a predefined tolerance. A narrow tolerance might be necessary in order to make the elements and the connections fit together but a narrow tolerance is however also more expensive. When it is not necessary to have a tight tolerance, a more generous one should be used. It is important to define the tolerances that are acceptable for an element and its connections. If the part to be assembled is not manufactured accurately it might be impossible to put it into place and to use the connections as intended. Connections must have a design that allows deviations within specific tolerances. Too small tolerances are not good regarding connection design.

Problems with tolerances are further discussed in a report by Linda Mattsson (2005). The author compares tolerances in building industry with tolerances in car industry. Undoubtedly, many building materials expand or in other way change in size which results in a need for larger tolerances in building industry than in car industry. Furthermore, there are generally two ways to handle tolerances. Firstly, size deviations can be taken by the last connection in e.g. a row of wall elements or, secondly, the deviations can be taken by every connection between the elements so they align with the elements underneath and above. The choice of solution depends on the current system.

Sustainability

One important part of sustainability is durability. The connection should be able to perform and fulfil its purpose during its service life. Therefore, it is important to have knowledge about the environmental conditions that the connections are exposed to. Different environmental conditions affect the structure in different ways and in different amounts. In order to make sure that a connection works correctly during its service life, maintenance might be needed. It is important that the design process includes maintenance. The cost for i.e. material in connections must be compared with the cost for maintenance during its service life. If maintenance is necessary, it should be easy to perform. Furthermore, the connection should not be too hard to access. No connections should need repair, only planned maintenance.

Additionally, buildings, including their connections, should affect the environment as little as possible during its lifetime. It should be effective with regard to material use, but also designed in such a way that deconstruction and recycling are easy to perform. It is preferred that buildings are demounted instead of demolished and for this reason the structural connections are important.

Notations

Below, the most important variables occurring in the report (text, equations, figures and tables) are listed in alphabetically order:

A	Assembly index
E	Assembly evaluation score ratio
E_a	Assembly efficiency
E_d	Design efficiency
G	Criteria grade
I	Importance factor
I_f	Fitting index
I_h	Handling index
K	Assembly cost ratio
n	Number of parts
n_A	Number of essential parts
$n_{\min}$	Theoretical minimum number of parts
P_s	Penalty score
p	Statement point
t_{acq}	Tool acquisition time

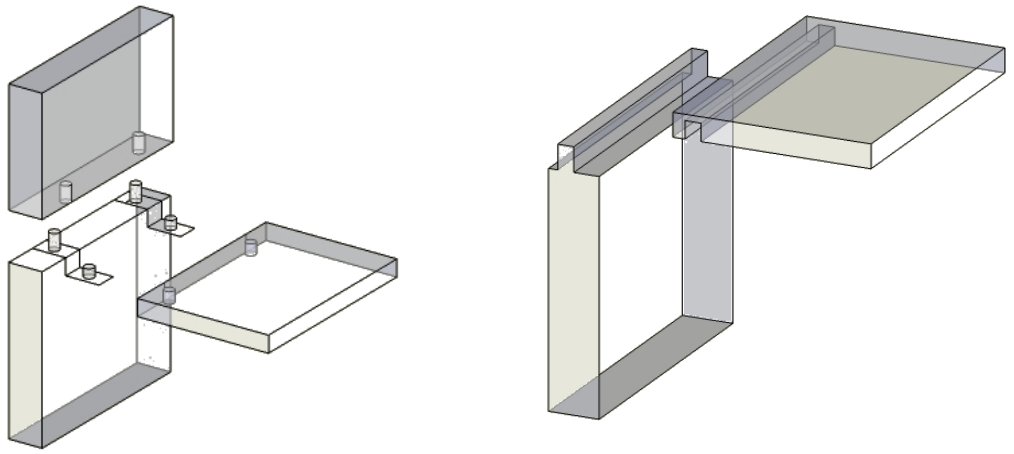
t_{ba}	Basic assembly time for one part
t_{ea}	Estimated assembly time
t_h	Time for handling
t_{in}	Time for insertion
t_{ta}	Total assembly time
α	Rotation angle, rotation perpendicular to the axis of insertion
β	Rotation angle, rotation around the axis of insertion

Product development in the building industry based on industrial thinking

This chapter focuses on standardisation of the communication process in the product development stage. The production phase in (building) manufacturing is often well-defined and predictable. The design and development stage is not. It has the ad-hoc characteristic recurrent in most creative activities. There is a conflict inherent in this. For example, in lean production, waiting and revising are considered to be two types of waste. In creative activities like design, it is important to allow for gradual improvements and for periods of lower activity when the work matures. In order for design, development and production planning to merge (which is one of the main aims of industrialisation), it is important that the design and development stage is structured. This chapter aims to do this in such a way as to not limit the creativity of the designers. It is based on the thesis *Product Development in the Building Industry Based on Industrial Thinking. Method for Connection Design* by Carl Jansson and Sven Tägtsten (Chalmers and NCC, 2007).

Definitions

Proper interaction between the elements in a house is needed because of many reasons. The most obvious reason is that forces should be transferred between the elements. Another reason is that a house should be tight against, for example, air leakage. The word connection, in a structural context, refers to the interaction between elements where loads are transferred. The interaction could either be discrete or smeared out. In a discrete connection the load is transferred through a clearly limited region (Figure 6 a). A smeared out connection convey that the load is transferred over the element length (Figure 6 b).

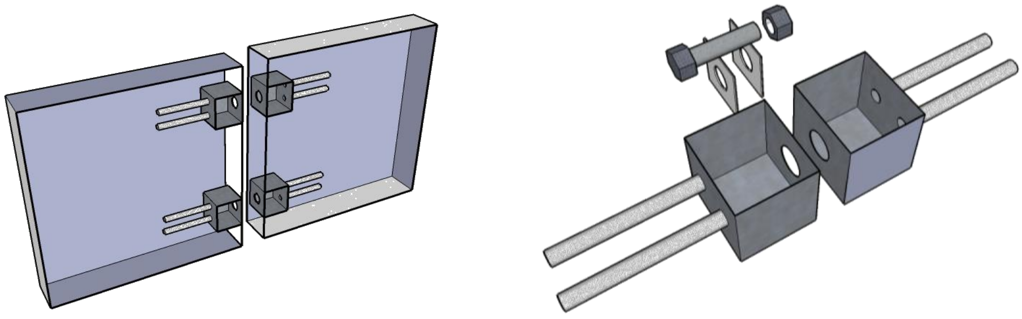


a) b)

Figure 6 Examples of different types of connections, a) Discrete and b) smeared out.

It may not always be clearly stated if a connection is discrete or smeared out. For example, tension can be transferred, between two elements, through a few discrete connection points. Compression can in the same situation, be transferred over the whole element lengths, in a smeared out connection. This demands the element developer to design their elements with respect to each load case, i.e. point load or line load. It is therefore important that the intended function of a connection is clearly stated for each load case. When the word connection is used in an air leakage context the connection is always considered as smeared out, since the air leakage cannot be hindered in a discrete connection. Tightness must be provided along the whole joint. This case is, however, of less importance in this section, since it mainly addresses structural connections.

In the report, we differ between the words *connectio*n and *connection device*. Connection refers, as earlier mentioned, to the interaction between elements where loads are transferred (Figure 7 a). Further on, the element region that is directly influenced by the forces (disturbed region and anchoring length of reinforcement bars for example) is also considered as a part of the connection. Connection device refers to the physical instrument that is attached to two or more elements, and whose purpose is to connect these elements (Figure 7 b). Connection devices can be discrete or smeared out. A connection must not consist of a connection device, e.g. welding or grouting could solve a connection but it is not seen as a device, it rather is a connection method.



a) b)

Figure 7 Example of a connection (a) and its belonging connection device (b).

Several connection types are needed in a building system in order to transfer all arisen forces. Another expression is therefore introduced; a *connection concept* refers to a group of connections, which includes all connections that are needed to take care of the arisen loads in a building system.

The Industrial Building Process

Industrial construction vs. traditional construction

In a traditional building process the aim of a new project is to develop and build a new product, e.g. a new house. In contrast to a traditional building process, in industrial construction the product is first developed and a project's aim is to build houses within the already developed product's frames. This can be seen as a development project and the developed product is a building system. When the product is developed projects can be built. A project in this case is one or many houses. This approach is used in traditional manufacturing industry, and therefore the name industrial building or construction. The projects that should be built within the system can be more or less adjusted to the current situation. One system may have only one standard house, and another system may allow changes in, for example, design and architecture. Today the freedom to choose between several options is seen as a very important parameter in industrial construction. This demand concerns the traditional manufacturing industry as well. For example, the person who wanted to buy a T-Ford in the early twentieth century could choose any colour, as long as it was black. If a car manufacturer today had such restricted freedom of choice for the customers the car manufacturer would not sell many cars.

A big difference when developing a building system, in contrast to development of a building project, is the possibility for development of new and creative solutions. The incentive to find new solutions in traditional building processes is, more or less, lost due to the fact that the project's contractor's aim is within the projects boarders. Product development is needed, but hard to motivate since each project's aim is to satisfy the customer's needs to as low cost as possible, in order to gain as big profit as possible. Product development may be too expensive in comparison to the project's budget.

In contrast to a traditional construction project where a predefined amount of buildings are planned, a building system aims to produce bigger quantities. Therefore, development of new solutions suits well and is of big importance in industrial construction, where all details have to be optimised in order to get as big profits as possible.

More over, it is also possible to improve a product in industrial construction. In a traditional building process that possibility is left out; to improve an existing house is only made if inconveniences are detected. It may also cause disturbance and be costly. If an inconvenience is detected in an industrial building product, on the other hand, there are possibilities to do the necessary changes before the next project is build.

The development process

When a building system should be developed it is important to investigate what the product should aim for. It is therefore important to do a product definition. This concerns all kind of product development; development of building systems and development of connections in an industrial building system as well as other kind of product development. Kahn et al (2005) has included the following parts in a product definition. The explaining notes are adjusted to fit development of a building system.

- Project scope, for example geographical restrictions, domestic or international.

- Specification of the target market, exactly which type of premises that are intended, such as housings, offices etc.

- Description of the product concept and the benefits to be delivered to the user, for example, a flexible system sets the customer in focus, allowing individual demands.

- A list of the products features, attribute, requirements, and specifications are set to emphasise particular parts and restrict the system. For example that a system should contain elements of a certain material and should not exceed a certain number of stories.

How well defined the product, i.e. the system, is may differ from one product to another. A well-defined product makes the development process more convenient and straightforward. On the other hand, a too well defined product may hinder creativity and innovative thinking and good ideas may be left out.

When the product is defined the development phase starts, the definition is evaluated and translated into certain proposals about what the product should contain; what is possible to do within the frames of the definition, resulting in concept solutions. Further on, the longer the development process reaches the more detailed the possible concept solutions will get. For every concept proposal investigations are made and solutions are evaluated. On the basis of the definition and those investigations, the number of suitable concept solutions is reduced as the development process proceeds.

For every concept, investigations about how details are going to be solved, have to be made. For example how the elements are going to be jointed together, which will result in connection development. When this question is of current interest it is time to initiate the connection development process. In which phase of the system development process the connection development starts may differ from one project to another depending on the connections role in the system. Consequently, if the connection has a central roll in the development process it is favourable to introduce the connection in an early stage. If a connection is of great importance and the development of it starts early it has a decisive function, i.e. it can set more demands on other components. It is then decisive for how the development process should proceed.

New Product Development

When a building system should be developed it is important to have a convenient development process. One reason is that a well functioning process results in an effective use of resources, which is a central point in industrial thinking. Another reason is the quality of the product; the product should correspond to the customer's expectations. In addition, an appropriate development process allows creative thinking, which is an important aspect of many reasons. This chapter aims to describe aspects of product development in a general perspective, not necessarily in building industry.

The idea can of course also be subdivided and implemented in development of certain components, as for example connections.

Product development with customers' needs in focus

The Danish architectural design studio Arkitema (Arkitema.dk) has developed a working method, called "sensemaking" for how customers should be involved in development of building projects, and how innovative thinking could be encouraged (Arkitema, 2006). The method is aimed to be used in a traditional building project. However, the development of a building system can be inspired of those ideas, since the purpose, to emphasise the customers' needs early in the development process is important in system development as well as in project development.

One purpose with the method is to detect the customers' needs, which may not always be clearly pronounced, and also to create conditions for a process that can fulfil those needs. The customers in this sense are the future tenants and users. If the customers should be able to explain their needs, it is preferable that they get inspiration from other buildings and solutions. Further on, the buildings' purpose, i.e. what activity will be pursued by the customers, should be emphasised in order to detect the unspoken needs.

In industrial construction the specific customers and their specific needs are not clearly known during the system development. The buildings can be more specific and adjusted to the specific client's needs in the project development stage. This can be compared to a traditional building process where the customer is more or less known. This means that a target market has to be decided, i.e. the range of customers must be set first, and after that the needs can be defined. The fact that the tenants are unknown demands the system to be flexible within the range of the intended customers' needs.

In development of connections and other components the customers of the system, i.e. the future tenants, are no longer the primary customers. Instead the primary customers are represented by the system itself and its developers. And the future tenants' demands are here only affecting the component development indirectly. One can say that, as long as the demands on the system are fulfilled the tenants' demands are fulfilled. In which way the components fulfil their requirements are not of interest for the tenants as long as the houses correspond to the product they wanted.

Articulated activities ease the development process

To get a well structured product development process without preventing innovative and creative ideas and solutions, it is important to have a general overview of how such development will precede. Rainey (2005) claims that the key to a successful product development is that activities within the product development is predefined and well articulated and that all participants and resources are well coordinated. The activity thinking is also stressed in Arkitemas method, “sensemaking” (Arkitema, 2006). The purpose is to describe each activity in order to clearly state what the task is in each stage. Since it is beneficial for planning of the development process to have an overview of what to do, it is necessary to know which activities that should be included in the process. Which activities that should be performed, and their purpose, can be stated from the beginning, whereas the actual content and procedure will be clarified during the process. One way to illustrate the different activities is with rhombus, where the first rhomb corresponds to the first activity etc. (Figure 8).

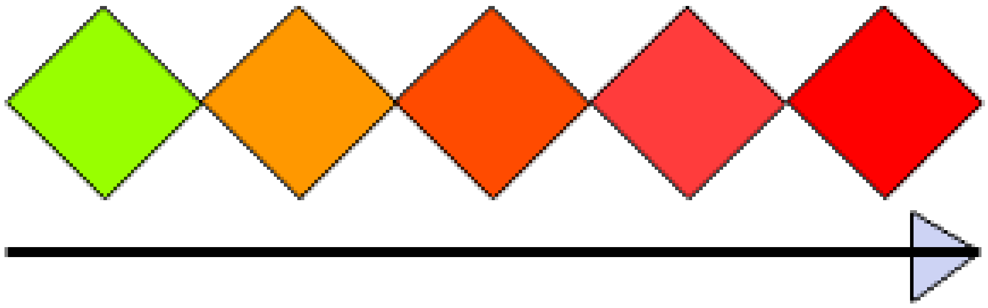


Figure 8 The activities in a development process illustrated as rhombuses.

The aim with an activity has to be clearly stated when it starts. An activity’s aim can either be “physical”, as calculating component dimensions or be “unphysical” as prescribing a definition or stating requirements. How the aim of an activity is fulfilled is not regulated, and the involved architects, engineers and other participants are allowed to use their creativity in order to produce innovative solutions. In addition to the aim, an activity starts with certain input data given from the previous activity, e.g. requirements or conceptual solutions. Moreover, in the beginning of an activity a working plan should be clearly stated. The plan should contain which task each participant has and also a time plan.

An advantage with clearly pronounced and predefined activities is that all involved actors of the product development know what result to deliver and when it should be delivered. Within an activity the involved architects, engineers and other participants have the possibility to think freely and are not restricted to anything else than the input data and what the activity aims to deliver. If the activity is not well pronounced a person may think that he/she has a lot of time to develop a couple of conceptual solutions. He/she might then do a rigorous investigation. When the project leader decides that

that particular part of the development process should be finished the developer have only made ruff suggestions, which do not compile with the project leader’s expectations.

Clearly pronounced activities make the work easier for the project leader, since he/she has a clear view over the projects progress and a clear assignment to conclude an activity and decide to begin the next one. In that case, “the point of no return” is reached. Such breakpoint corresponds to where the involved parts confirm that their performed work fulfils the aim and that the project leader confirms that the next activity can begin. The risk with a process without any predefined activities is that resources are incorrectly distributed and that a too distant deadline reduces the motivation. It is easier to work effective when the goal is reachable. More over, when the task is clarified all irrelevant work can be rationalized and the focus can be on the real task. Further on, it is necessary to have well defined activities in order to coordinate different actors. Otherwise, one actor may put in a lot of effort to complete his/hers task, but has to wait for data from another actor that have not completed his/hers task; the actors’ work is out of phase.

If no activities are predefined no breakpoints, with compatibility control with the rest of the system development, are planned. Hence, there is a risk that mistakes and miss aimed choices may be detected too late. In worst case, an early made choice that is not compiled with the rest of the development, will affect the following work in such great extent that big efforts must be used in order to recover the mistake. The consequence will be a product that does not comply with the aimed one.

A broad view gives better solutions

The fact that the approach in Section 3.2 suggested a development process that is irreversible, in the sense that when an activity is ended there is no turning back, forces the actors to produce the “right” solution from the beginning. This demands a high quality level on all solutions that are delivered at the end of an activity. Hence, it is very important that the first activities are “broadening the view” of the project; interpret the aim with the project, do researches about the subject and needs from the intended users and gain knowledge about how different decisions will affect the consecutive work. Ottosson (1999) means that to be able to find solutions for user- and usage demands, one has to abstract the task before more concrete solutions are chosen. This to allow that a lot of possible solutions are treated instead of choosing the solution that is most common. It may turn out that the common solution is the best after the evaluation, but at least it has been more critically reviewed in that case.

The approach to first broadening the view and then align to a more detailed solution is applicable on activity level as well as on project development level. This means that when an activity begins the situation is very clear; one knows what to deliver and within which frames, on the basis of the previous activity’s results. One can think that the progress in this situation should be to, as fast as possible, find a proper solution that suits the activity aim. This may, however, exclude many other solutions that will fit the aim as well. It is important to have a methodical progress; the first idea may not be the best even though it has worked before in a similar situation. Instead, the developers should be patient and come up with several possible solutions and investigate their consequences.

How and when to make decisions

It is important to beware of how different decisions procedures will affect the development process, i.e. many small decisions or a few big decisions. Ottoson (1999) argues for that many small decisions promote an effective process due to the fact that the importance level of a single decision is decreased. This allows decision making on a lower level in the organisation, i.e. each participant of the process has more influence in the decision making, and the need for a detailed long time planning is not demanded. This also spreads the risks and if one decision is wrongly made the process for correcting it becomes easier; one can say that the process is dynamic. The opposite of the above mentioned decision model is the centralised decision model where all decisions are made higher up in the organisation; this leads to fewer and bigger decisions which increase the risks for big redoes if it turns out that a decision is not optimal or wrongly made. This also demands a detailed long time planning and the flexibility of the development process may be hindered. In addition to that, it is harder to affect the development for participants lower in the organisation. The process becomes more static than when process allows small decisions, as described above. In order to ease the communication within an activity, as well as avoiding the above mentioned risks with to infrequent and big decisions, each activity should have continuous and close in time breakpoints.

Quality assurance

The communication process can be seen as a quality system, where each step in the development has to be approved. For each phase in the development stage each developer has to assure the quality of his/her component, i.e. make sure that the given requirements and evaluation criteria are fulfilled, which can be seen as a self check. In some stages the component’s quality has to be assured by someone with an overview of the whole system, i.e. the product development group. This quality check should assure that the component is compatible with the rest of the system. Since the development of the system is an iterative process the conditions may change during the process. These changes may as well change the demands on the components. It is therefore important that someone with an overview of the entire system can communicate new demands to the component developers and make sure that the demands are fulfilled after each stage. If the developers work on a connection on the basis of demands that are not up to date much work are done without actual progress. This can be compared with “over the wall design” (Boothroyd et al, 2002) where the designer creates drawings without feedback from the manufacturing engineer, which leads to the fact that the manufacturer must deal with all arising manufacturing problems because he/she was not involved in the design phase.

In order to re-call the ideas from Section 3.2 (the development process should be divided into activities), and to couple it with the quality assurance, each break, between two activities, should function as a quality control. This is illustrated in Figure 9. Each activity is iterative with clearly stated breakpoints between the activities.

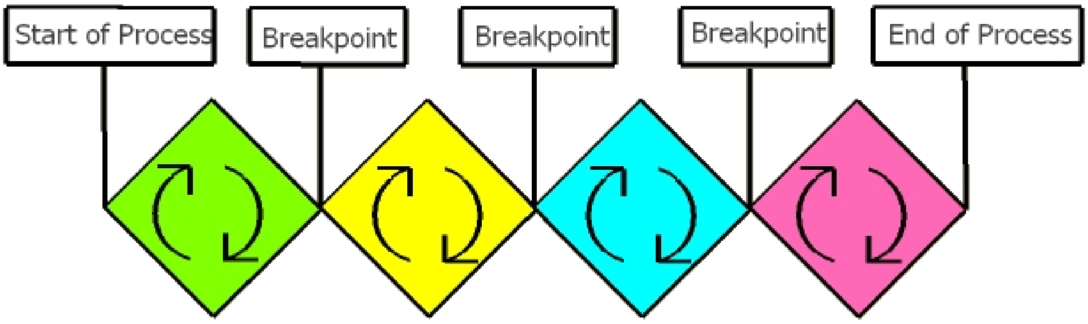


Figure 9 The activities in the development process are iterative. Clearly defined breakpoints are stated between the activities.

In addition to assurance of the quality the breakpoints should function as project break points. It is well suited to put the question: can this development process be result in a product that provides economical profits. Without clearly stated breakpoints it is difficult to end a development project, even though it seems to have small opportunities to succeed.

How to Judge Connections – Requirements and Criteria

Two approaches to judge a connection are stated in this section. The first approach is to judge on the basis of absolute requirements. These requirements can be judged with a “yes” or a “no”. All absolute requirements must be fulfilled for a connection that is acceptable. The absolute requirements are divided into two groups, authority requirements and system-regulated requirements. The other approach to judge a connection is on the basis of evaluation criteria. These criteria cannot be judged with a “yes” or a “no”. These criteria can be fulfilled to a high extent or a low extent. An evaluation criterion may be very important for the system or it may be less important.

Absolute requirements and evaluation criteria can either be quantitative or qualitative. Quantitative means that an actual number can be set on the requirement or the criterion, e.g. the connection should be assembled in ten minutes. Qualitative means that the judgment is made on the basis of non-measurable parameters, e.g. an architect judges a connection on the basis of how well it fits into the system from an aesthetically point of view.

More over, an evaluation criterion can be converted to an absolute requirement if an absolute limit is set. For example, an evaluation criterion is that the connection should be fast to assemble. When more information about the system becomes known it is decided that the connection, which should be chosen, should be assembled in ten minutes.

This chapter aims to describe different types of absolute requirements and evaluation criteria concerning connections. Notice that the number of requirements and criteria that can be set on a connection is more or less immeasurable, and hence the authors do not have any intention to find or list all of these.

Absolute requirements

The primary safety requirement on a building is that it should not collapse during its service life, which off course can be applied to the connections as well. Therefore, a connection design has to fulfil certain requirements from norms, regulations and standards.

Other requirements that are decided on the basis of regulations and that concerns the connections are for example sound and indoor climate. These requirements have a certain limiting value that must be reached and that are valid for buildings constructed in factory as well as buildings constructed with traditional methods. These requirements are regulated for the whole building and should be sub-divided to requirements on the components.

The connection’s role in the structural system

From the absolute requirement that the building should withstand all conceivable actions during its service life, an idea follows of how the structure is going to take care of these actions. The idea of the structural behaviour gives the requirements on component level, e.g. connections. The opposite is also possible, that the components set requirements of how the structural system should be designed.

The connections are intended to withstand different types of action, shear forces, normal forces and bending moments for example. These actions are directly linked to the building’s structural system.

Load bearing capacity

There are two main load directions that a building has to withstand, horizontal and vertical. The first mentioned arises mainly from wind loads, inclined elements (intended or unintended), imposed loads and accidental forces and should be resisted by stabilising functions transferring the loads to the ground. The latter one arises from self-weight, snow loads, imposed loads and accidental loads and should be transferred through the structure down to the foundation. All of these loads have to be resisted by the house. In addition to these actions, the design must consider that the building is affected by different types of loads in different stages of the building process. An example is when a wall element is designed to be stabilised by an adjoining element, but before the adjoining element is assembled the wall element has to be self stabilising, which causes new requirements on the connection, i.e. it should also be able to withstand moment forces.

Moreover, it is important that buildings perform during their whole service life. Therefore, buildings as well as connections have to be designed to be accessible, in order to do inspections and maintenance work.

Evaluation criteria

In order to be able to choose a suitable connection that fits the system well, evaluation criteria are set. Every criterion must not be perfectly fulfilled for the chosen connection. Instead the emphasised criteria should be fulfilled to a high extent and the criteria of less importance must not be fulfilled in such high degree. Therefore every evaluation criterion must be weighted with regard to its importance to the system. The importance should be chosen on the basis of what is emphasised in the system definition. Moreover, it is preferable to have a minimum value of what a criterion should fulfil. Evaluation criteria can occur from different sources.

The first source is the system; what must the connection fulfil in order to fulfil the absolute requirements and evaluation criteria on the system? An example is: how thermally tight must the connection be, in order to fulfil the requirement on a minimum indoor temperature? The indoor temperature is an absolute requirement, regulated in codes, and all building parts and components must cooperate in order to fulfil the systems absolute requirement. Hence, it is off course preferable that all building parts perform as good as possible. The system's absolute requirements are translated to evaluation criterion concerning the different building components, e.g. the connections.

An example of when an evaluation criterion concerning the system is transferred to an evaluation criterion concerning the connections is when a connection should be judged from an aesthetical point of view. The system should be judged on the basis of an aesthetical criterion and, hence this criterion has to be translated to connection level.

Further on, the second source of the evaluation criteria is other criteria on connection level. An evaluation criterion or an absolute requirement is translated to several sub-criteria when they are more specified. An example is that the connection should be sustainable, which can be translated to the criteria for inspection possibilities and maintenance work possibilities.

Evaluation criteria occur during the whole development process, it is more or less impossible to list all necessary requirements from the beginning. New evaluation criteria must therefore be clearly communicated to all concerned people.

Requirements connected to prefabrication

The basic idea of prefabrication action is to have no, or little, supplementary work on site. This result in a high level of completeness of the elements when delivered to the building site, therefore traditional jointing methods such as, welding and grouting should be avoided. The main reason is that these are time-consuming activities, which does not agree with the basic principles of industrial construction. Another reason is that they may pollute the more or less completed elements at the building site. Wallpapers, kitchens and other sensitive parts must be covered or cleaned when a polluting jointing method is used. This leads to more supplementary work.

A connection that agrees with the basic principles of industrial construction should be easy to assemble; a method for doing such a design process is called DFA, Design For Assembly. In this project, a DFA method for building manufacturing has been developed and is given below (and in Jürisoo and Staaf, 2007). In addition, there are similar methods for, for example, manufacturing, DFM (Design For Manufacturing), which can be used depending of what the product is aimed for.

Assembly of elements demands smaller tolerances than traditional in-situ construction, since the elements are already fabricated and must fit together at assembly. In traditional on-site construction deviations can be corrected during the building process. In contrast to that, in industrial construction a deviation may cause, either that elements cannot be assembled or that the deviations are propagating, i.e. a small deviation on component level may propagate and cause major displacements on structural level. This issue can be solved with two approaches, a flawless planning and manufacturing or with connections that can handle the deviations. A perfect system does not allow any manufacturing mistakes and may be difficult, or even impossible, to achieve. Therefore, it is preferable that the connections tolerate deviations. However, the tolerances are tighter and more important to fulfil than in traditional on-site construction.

Except from that the connections should function in the structural system; they must as well withstand all conceivable loads during the assembly process, i.e. connections must be designed with regard to the intended assembly method. An example is, before a stabilising wall is assembled, adjoining elements must be able to be self stabilising if no temporary bracings are intended.

Another issue that has to be considered is the manufacturing method. A method for designing for manufacturing is, as earlier mentioned, called DFM. To consider manufacturing early in the process is important since it is necessary to develop a connection that is possible to manufacture. It is also easier to optimise the connection regarding manufacturing when the issue is considered early in the process.

Connection requirements on the system

This chapter has mainly described how the system sets demands on the connections. It is however important to explain that the opposite is possible as well. For example, if a wall element should be lifted in the connections, it must be designed with regard to that load case. These requirements can be decisive for which connection that should be chosen. A requirement that affect the system too much may exclude that particular connection. It is therefore always necessary that the requirements are clearly stated and communicated to all persons concerned.

Connection Development – the Containing Activities

As mentioned above a successful product development process demands well- articulated activities. This chapter aims to describe four well-articulated activities, which suit well for connection development. The activities that are chosen are: *Definition,* where the structure of the development should be stated. *Conceptual design* means that a couple of solution should be invented. *Evaluation and improvements* aims to select the best conceptual design. *Detailed design* aims to do the final design. The activities are illustrated in Figure and are described more comprehensively in this chapter. One important aspect during the development process is the information flow between the system development group and the connection development group. This information flow is visualised with arrows in Figure 10. It should be emphasised that these activities may not be suitable in all situations and that the activities should always be optimised with regard to the current situation.

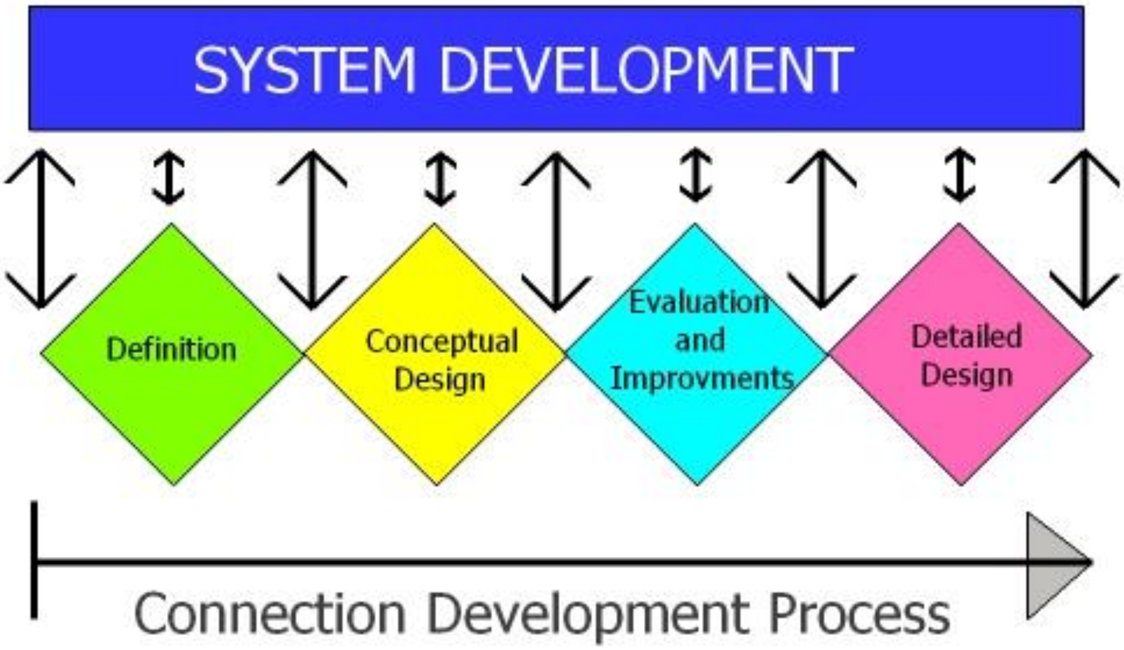
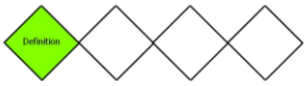


Figure 10 *The connection development process with the including activities illustrated as rhombuses. The arrows illustrate the information flow between the connection development and the system development*

Definition



Two sub-activities in the definition activity can be found. The first one concerns a definition about how the development work should be treated, which activities that should be included in the process, how responsibility is divided, how the information is going to be shared and other effects that concerns the development process. The second sub-activity concerns the connection itself. It can be seen as a translation from the system definition into basic conditions that are decisive for the connection development, e.g. level of flexibility. These sub-activities are dependent on each other, they should, hence, be carried out parallel.

Structure of the connection development process

Forming a group

Firstly in a development process a project group has to be organised. There are several important group psychological issues to be aware of when a group should be composed (Monplaisir and Singh, 2002). Monplaisir and Singh claim that a well composed group can perform much better than one individual can do, since many professions, knowledge and approaches can be gathered. However, there exist traps that one has to be aware of when putting a group together. Monplaisir and Singh emphasise four major reasons why groups do not perform as well as expected: *Participation*, everyone at a meeting can not talk at once, which leads to unnecessary waiting time. *Conflicts* can reduce the communication between participants and winning the conflict becomes more important than making the right decision. *Group think* is when members are pressured, for different reasons, to get along with the other members, and the decisions can become incorrect because no one argues with the made decision. *Group polarization* is a phenomenon that means that members' opinions tend to be more extreme than they originally where. These reasons, of why groups may not always perform as good as expected, should however not lead to the conclusion that groups should not be used in development processes. These reasons should instead lead to the conclusion that groups should be used with consideration about problems that can occur. Ottosson (1999) claims that a project development group should be located at the same geographical place, in order to reach as good results as possible. This will encourage informal meetings and shortening the communication paths. This may, however, not always be possible since development processes concerning a building system contains people from several companies and they may have other parallel work assignments. It should be stressed that technology has developed since the book was published. It is easier today, with help of modern technique, to work on different geographical places.

The connection development group must contain several professions and qualifications in order to utilize the benefit with a development process group. The professions should, for example, contain knowledge about acoustics, structural engineering and indoor climate, and in addition people that have knowledge about and responsibility of the elements in the system. The leader of the connection development group should have influence of the system development, since there must be a continuous communication process between the system development and the connection development.

Planning the process

The second thing to decide is which activities that should be included in the process. Different circumstances demands different project organisation and the project plan should off course be optimised to fit the current situation. Before the definition activity is concluded the approach of the following activities can be changed. The aim with each activity should be decided during this first activity. The actual content of an activity may however be decided in the beginning of the activity. When the activities are confirmed by all participants a time schedule should be set; when each activity should begin and be finished. Since the development process may go on over a long time a detailed time plan cannot be set in this stage. A more detailed time plan for an activity can be set in the initiation phase for the activity. The time plan must be coordinated with the time plan that is set up for the system development. This means that the connection development time plan is very restricted and must be adjusted to the general system development. To know when a connection development activity can start and end it must be analysed when certain system related decisions and activities are made and concluded. It is, of course, preferable to do this analysis already in this early stag. It may however not be possible. As the system and connection development processes proceed the more the time table can be accurate.

Responsibility distribution

Responsibility distribution is another important area that must be clarified in the definition activity. It may, however be difficult, or impossible, to decide the responsibility distribution within the latter activities. It may not even be known who the people that participate in the latter activities are, since different professions are wanted during different activities. To have the same people during the whole development process is preferable, even though it may not be possible in all situations. When different groups take care of different activities, called over-the-wall product development model, there is a risk that much work has to be redone, and unnecessarily efforts are spent (Trott, 2002). Hence, it is suggested that, at least, a core of the development group should work continuously through the whole process. This will lead to that the group has an understanding of earlier made decisions and superfluous time to questioning previous work disappears.

Information exchange

Another important decision is how the information flow should be treated. The most obvious reason, for a well functioning communication process, is to make sure that the participants work with conditions that are up-to-date. Another reason, maybe not that obvious, is that the development group should have a possibility to follow up previous made decisions, and their influence of the development process. Lessons of mistakes made can be learned and the next development process can be better and more effective. Ottosson (1999) suggests that every participant in the development process should make diary notes for every progression in the development. These diary notes can be important in the future, if for example juridical disputes concerning patent-rights and other issues occur. Ottosson (1999) also suggests that the participants should write a weekly report, which should be handed out to all other participants, where the progression and the discrepancies should be announced and also a suggestion about what the work for the next week should contain. The weekly reports could for example be handed out via internet, mailing-lists or web pages with access for the development project’s participants.

On the basis of these weekly reports the project leader should make a development project report. When the development project is finished conclusions about the development process can be made. This feedback of knowledge and experience suits well with the idea of industrial thinking. The authors do not prescribe that the reports should be weekly, but does however emphasise the importance of continuous report. The report of the connection development can, however, not function alone, a system of how system development process is reported should already have been stated and the connection development report can be an emphasised part of that report.

One essential thing that should be communicated is the requirements and evaluation criteria on the connections. To list all requirements at this early stage may be very difficult or even impossible. Ottosson (1999) means that a list, with predefined requirements, makes the product development group relaxed and less alert. Instead a list should be prepared during the first activity; it should then be filled in during the development process, when more information about the system and the connection becomes known. A convenient method is to explain all new requirements in the reports that are carried out continuously and at the same time add them to the requirement lists. The requirements can then be installed into a table where it is shown which sub-development that is influenced by which requirements (Ottosson, 1999). An example of such table is shown in Table 1. This table should be stated by the system development group, since it concerns all sub-developments.

Table 1 Table that shows which sub-development that is influenced by which requirement.

	Sub-development			
	1	2	3	4
Req 1	X		X	
Req 2	X		X	
Req 3	X		X	
Req 4		X	X	
Req 5		X		X
Req 6		X		X
Req 7				X
Req 8			X	X

Information exchange does not only exist in written format. Important decisions are often made during meetings. It is important to have a strategy and a plan of how, and when, meetings should be organised. In some cases it may be preferable to have weekly meetings and in some other cases it is better to have meetings in crucial stages. It is very important to have meetings when an activity starts and when it ends. The concluding meeting for one activity can be organised in combination with the start meeting for the next activity.

An important aspect about information exchange is how the information should be shared between the connection development group and the system development group. It is essential that both groups are working on the basis of the same information. Similar development processes, e.g. about wall- and floor elements, are going on at the same time. Hence, it is preferable that some of the people participate in both the connection development group and the system development group. This will reduce the risk of an “over-the-wall process” (See Section *Responsibility distribution*).

The connection

During the same time as the definition concerning the connection development process is set the connection development group should set a definition concerning the connections. The connection definition can be seen as the aim with the connection development. As described in Chapter 2, a definition for the system is set in the beginning of a development process. The definition can be interpreted and basic conditions that are decisive for the connection development can be identified. Examples of basic conditions that are decisive for the connection development and directly implemented from the system's definition are:

- *Type of system: planar, skeleton or volume elements.*
- *Level of flexibility: how flexible should the system be, widths, heights etc.*
- *Multi functionality: should an element type be universal or should the system contain several different element options that all are optimised to fit its specific task.*
- *Importance of fast assembly: assembly is decisive for the system design, and connection details are therefore emphasised.*
- *Importance of a certain element type: the system design depends in big extent on a certain type of element.*
- *Architectural aspect: may restrict the system and exclude solutions on connections and elements.*
- *Economical aspect: how crucial is the connections for the system, and how large resources can be put on development of the connections.*

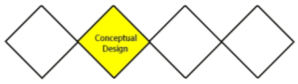
These basic conditions concern the building system. They can however be translated to requirements and criteria concerning the connections. Chapter 4 described that two approaches for judging connections are possible, evaluation criteria and absolute demands. The basic conditions mainly results in evaluation criteria. It is therefore important to investigate how important the different criteria are.

The greatest difference between system definition and connection definition is the importance of having the customer in focus in the system definition. The system's regular tenants do not care of the connection design, since it mainly is a technical detail. This means that one aspect that is of great importance in many product development methods disappears, which thus means that the focus in connection design should be on fulfilling the system definition.

During this activity, it is important to do investigations about the consequences the connection definition will give for the system, for the connections and for the development process. The proposed approach is to presume basic conditions and then simulate the consequences in order to find out as much as possible about the made choices. The procedure is repeated until the connection development group have found a definition that is achievable and that fits the system definition. This can be seen as a trial and error procedure.

Another important aspect, which should be considered in the definition activity, is to do a risk analysis. This is done in order to predict eventual mistakes in the design and predict risks from the world around, such that a deliverer can go bankrupt. When the risks are detected, a plan, of how to handle the eventual risks, has to be stated.

Conceptual design



After the definition is set the actual development work can begin. The aim with this activity is to come up with a few (but not a predefined number) conceptual solutions of how the connections can be designed. This is a very crucial stage in the development process, as described above it is important not to run into, and work on, the first solution that comes up. Ottosson (1999) emphasises the importance of not trying to find detailed solutions early in the development process, since it blocks the creativity. In contrast, the first part of this activity should contain a discovering phase; discovering about existing solutions and about what consequences the solutions will bring to the development process. In addition to discovering the first stage of the activity should contain a brainstorming phase. It is then not necessary to look directly on the definition; the important aspect in this stage is the innovation and the creativity; to come up with many ideas. One can say that the quantity is more important than the quality, since the irrelevant solutions will get rejected later in the process. Ottosson (1999) suggests that during a brainstorming meeting, when the creativity is inhibited and no innovative ideas come up, the project leader should give a “crazy” idea since it can ease the dialog and trigger the creativity.

When the group has come up with several conceptual solutions the next phase is to eliminate the misaimed ones. If the product development group has worked creative and has come up with many solutions there are most likely many that can be rejected with no further discussions. The further evaluation is going to be carried out with help of the evaluation criteria that were set in the first activity. It is important to emphasise that it is not only one solution that should be chosen in this stage, instead at least a couple of promising solutions should be elaborated. To develop several connections parallel means that important decisions about the connection design can be made later in the process, when more information about the system is known, which means that the risk of impropriate connections is decreased, which can be seen as a quality enhancer.

To do conceptual design on a couple of connections, when only one is going to be chosen, can seem as a waste of time and resources. Above, it is explained that the quality aspects is one reason why many connections should be handled. Another reason is that the concepts can be used for future system development processes. A company can gather the concepts in a connection bank and the concepts can then be reused in the next connection development process.

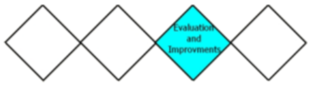
The cost for developing concepts is easy to predict, since the cost is mainly connected to the participants’ salaries. Ottosson (1999) claims that the costs for the stages before the prototypes are constructed should, and can easily, be kept at a low level.

Meanwhile the connection is developed the system and its containing elements are developed. This and the fact that the connection design is directly dependent on the system design lead to several important conclusions. The first is that the communication between the two development groups is very important. The connection development group has to do conceptual solutions on the basis of the correct input. If for example the connection development starts early in the system development process, when little information about the system is known, the connection development group may have to wait for information from the system development. Hence, the conceptual design is not continuous; several, shorter and longer intermissions can occur. This emphasises the earlier mentioned conclusion that the progress of the first phase within the activity, discovering and brainstorming, should be slow. The less information that is known, the slower the progress should be and the broader the view must be. The information from the system development is often transferred continuous during the connection development process. Another approach is also possible, that all major decisions concerning the system design are made already before the connection development starts, in that case the connection development group has much input data to work out of and the progress can be more concentrated and rapid. One of the most important decisions that have to be made, in order to be able to develop the connections, is choice of structural system; how the loads, horizontal and vertical, should be taken care of. If, for example, the structural system is not chosen before the conceptual design starts more solutions have to be invented, since different structural systems demands totally different types of connections. In that case, the solutions can be divided in different groups, e.g. one group that demands the system to consist of concrete walls, and another of framework of steel. Every solution sets requirements on the system, on the basis of those, and other requirements from other sub-development processes, the structural system can be chosen. This is, however, a decision made on system level. Consequently, the requirements on the system from the connection development must continuously be reported to the system development group. When the system development group has made a decision, about which structural system that is chosen, the progress, of the connection development, can be much more concentrated and also faster.

As explained above, the connection development can gain more knowledge dependent on how far the progress of the system development has reached. Thus, the activity must be iterative; when new information becomes known the concepts may have to be redone.

Another issue that has to be considered in this activity is the difficulty to know when the conceptual solution activity can be concluded. It is of great importance that the system has reached a certain degree of development. Otherwise, great problems can occur. For example, if the connection development has resulted in three connections that all requires a framework of steel, but the system development group has not decided that a framework of steel is the best structural solution. In that case, the connection development has had a too fast progress. A convenient rule is that the conceptual design activity never should be concluded before the structural system is defined. It should be emphasised that in some cases the structural system may have been defined already before the connection development starts. There might be other important decisions on system level that have to be made before the conceptual design of connections can be concluded, and these must of course be communicated to the connection development group, in as early stage as possible. A check list with decisions that has to be made in order to conclude the conceptual design should be set up.

Evaluation and improvements



The aim with this activity is to go from a few connection concepts, which where the result of the conceptual design, to only one concept, which is the one that should be used in the system. To achieve the aim with the activity all concepts should be evaluated with regard to the criteria, and the definition, that have been stated in the earlier activities. Different evaluation methods could be used in order to choose the best solution. The final decision can be made when a real sophisticated evaluation system that considers all aspects of the connection design, and the connection design's affects on the system, has been used.

Evaluation methods

Different evaluation methods should be used in different stages. In the beginning of the activity the evaluation can consist of judgements by experienced people. The judgments should be on the basis of the criteria that are set up. These judgements may reject some connection solutions. They may also exclude evaluation criteria if all connection concepts are similarly judged regarding a certain criteria.

As the activity proceeds the methods should be more sophisticated. A sophisticated evaluation method should be able to weight the different criteria with regard to their importance to the system. Weighting can be done in different ways. The most convenient way is to set grades on the criteria; an important criterion gets a high grade and an unimportant criterion gets a low point. The weighting could also be more accurate as the activity proceeds, when more information about the system becomes known. However, the connection definition should always be the foundation of the evaluation. Jürisoo and Staaf (2007) have developed a method (described in detail later in this report) for evaluating connections with regard to easy assembly. The method consists of sixteen criteria that each should be weighted from zero to two. Each criterion consists of three statements, which is given the points -1, 1 or 3, and the statement that best represent the connection should be chosen. This method could be redone, so that it covers other areas that have to be considered as well. An example of a criterion is shown in Figure 2.

Stability		IMPORTANCE: 0
Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		
Comments and assumptions:	*The element is stable with no help from the studied connection.*	

Figure 2 Example of a criterion for evaluating connections with regard to easy assembly, Jürisoo and Staaf (2007). See Appedix A.

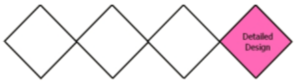
Testing

Another method to evaluate the connections is to perform tests. Testing can be made in different ways. The most obvious way is full-scale trials. This is however an expensive method that is best used in the latter part of the activity. Before real-life tests are carried out simulations ought to be done. A convenient way to test the solutions is with help of VR (Virtual Reality) simulations, which can simulate assembly order and identify problems that can occur. These tests should of course be a help to evaluate and reject connections.

Improving the connections

During this activity the design of the solutions should be improved. The evaluation can show that a connection solution has a certain problem area and if that problem area can easily be fixed there is of course no reason to wait with the improvement actions. In contrast, improvement actions are very important actions in this activity.

Detailed design



This activity aims to do a design that can be directly implemented in the system's future projects. The design should fulfil all requirements and criteria in the lists. It is important that the connections are designed with regard to the correct load amplitudes. Hence, parameters from the system must be known, e.g. height, widths and wind loads. It is important that this issue is considered earlier in the process and assured that the chosen solution can handle all forces; in other case the development has to be redone. Further on, it should be decided where and in which situation each connection fits, e.g. in a house with four storeys: chose version one, and in a house with eight storeys: chose version two.

It is also important to make the connections ready for manufacturing. The connection device itself should first of all be manufactured. In addition to that the connection devices should be implemented in the element manufacturing procedure.

Guidelines – Method for Connection Development in Industrial Construction

On the basis of the chapter above where a new product development process with containing activities where discussed, this chapter aims to present guidelines that can serve as a help for a development group during the development of connections in an industrial building system.

General advice for connection development

General advice that should ease the connection development is presented in this chapter. This is given as general advice since it does not belong to a certain activity; the advice is rather valid through the whole connection development process.

- The leader of the connection development group should have a good knowledge about the system development; he/she should preferably be part of the system development group. It is also preferable that the other members of the connection development group have an insight in the system development. This is important since it will ease the communication and create an understanding of the decisions made in the system development group.

- The members of a group and the group structure are important parameters for how successful a project will be. Therefore, it is preferable that the leader of the connection development group has knowledge and experience of how groups should be organised and what type of personalities that are needed to form a successful team.

- It is preferable if the project development team contains the same members through the whole development process. This will rationalise the process; the members has an understanding of the preceding development process and earlier made decision does not become questioned unnecessarily.

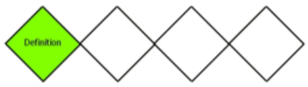
- Keep a journal; it is much easier to follow up and understand the process afterwards if every decision is noted. Another aspect is if discrepancies, with for example juridical context, appear. In that case it is favourable to be able to show how the progress of the process has been carried out. With help of the journal a follow up could be carried out, which will point out mistakes and other things that could be learned. The journals should be compiled in a project report, which could ease future connection development processes and make it more efficient.

- Save conceptual solutions for future development processes. They might suit well in a future building system.

- Predefine which activities that should be included in the development process. The following chapters give a suggestion of four activities that could be used in the development sections. Each activity should start and end with a meeting. The start meeting should give the involved members the conditions for how the aim of the activity should be reached and the end meeting should confirm that the activity could be included.

- Each activity should be iterative. The development process is, however, not iterative. Each start and beginning of an activity is a clear breakpoint. When an activity has started the possibility to go back to the former activity is lost. A breakpoint is also a good opportunity to decide whether the development process should continue or not.

Definition of the connection development



The first activity is called definition and the aim is to state how the connection development process should be carried out and to make a definition of what the developed connection should fulfil. The definition activity is divided into two sub-activities; the first sub-activity concerns the structure of the development process and the second concerns the connections themselves and should result in a connection definition, which is a translation of the system definition.

Structure of the development process

- The group leader’s first task is to organise a group with needed professions and personalities that fits each activity. A responsibility distribution within the group should also be set, i.e. the members’ tasks.

- State all containing activities in the connection development process and confirm them with the system development group. Decide what should be delivered in the end of all activities, i.e. the aim with each activity. A time plan, should be stated, which needs to be coordinated with the system's time plan.

- State how information should be delivered: how the participants should be informed about necessary news, mailing lists, meetings etc.

- Initiate a risk analysis in order to detect possible inadequacies with the design, and how these could affect the building system. Both inadequacies within the system and outside. An example of risk analysis within the system is what the consequences will be if one connection fails during its service life. An example that concerns the system development indirectly is the effects of rising material prices or a contingent bankruptcy of a connection manufacturer. The risk analysis should be further filled in during the development process.

- State which documents that should follow the development process. Suggestions of documents are presented below:

    - *Absolute requirement table:* All requirements that can be judged with yes or no are included in this table. All requirements should be fulfilled for an acceptable design. An example of such table is shown in Table 3.

Table 3 Example of what an absolute requirement table could look like.

Nr	**Absolute requirements** The connection should…	Fulfilled Yes/No
A 1	Be able to resist all applied forces	
A 2		

    - *Evaluation criteria table:* The aim with each criterion should be set. An example of such table is shown in Table 4

Table 4 Example of what an evaluation criteria table could look like

Nr	**Evaluation criteria** Parameters:	Aim: The connection should…	Comments
E1	Visibility	Not be clearly visible	Supplementary work may be necessary
E2			

- *Activity completion table:* State which tasks and decisions that should be made in order to conclude an activity. The table should include which actor that can approve if the task or decision is fulfilled. The aim with each activity can be included in the table already at this stage. An example of such table is shown in Table 5.

Table 5 Example of activity completion table, an activity can be concluded when all sub tasks or decisions are made, i.e. when the boxes of interest are ok.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	
2	Come up with a couple of connection concepts		X	
3	Select one concept.		X	
4	Optimise the connection and make it ready for manufacturing		X	

- *System requirement table:* A connection can set requirements on the system. These requirements should be inserted in the system requirement table (Table 6). The system development group should latter decide if these requirements are acceptable.

Table 6 Example of system requirement table.

Nr	**Requirement on the system**
S1	The floor elements should be reinforced in the top at the supports
S2	

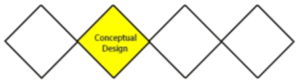
Definition of connection

- Implement basic conditions from the system definition that are decisive for the connection development and investigate how these basic conditions will affect the connection development process. This should preferable be done at the same time as the different activities are stated, in order to optimise the activities with regard to the basic conditions.

- Translate the system definition to requirements and criteria concerning the connection. Investigate how the requirements and criteria will affect the development process with a trial and error procedure before they are completely stated. Separate absolute requirements and evaluation criteria and include them in the tables. Assembly should be stressed in an industrial building system and is directly coupled to the connection development, and hence should the assembly be stressed at this early stage.

- Make a definition; a short text where the aim of the connection development is stated. State which evaluation criteria that are important.

Conceptual design



The aim with this activity is to produce a few connection concepts that agree with the earlier stated connection definition. The *conceptual design* activity is the most time consuming activity and most of the development work is going to be performed in this activity. It is likely that several system concepts are investigated. It is therefore convenient to perform a connection development process for every system concept.

- The fact that conceptual design is the biggest activity means that the activity needs proper planning. Divide the activity into sub-activities. It is preferable to state in which sub-activities information from the system development group is needed. For this development process the following eight sub activities are suggested:

    - *Brainstorming:* To find a lot of innovative solutions and not hinder creativity it is preferable to start with a brainstorming stage where all imaginable connection devices are welcome. It is not necessary that all ideas are good; a crazy idea may give birth to a good idea. The ideas that do not fit will be rejected later. Avoid searching for the “right” solution immediately. Inspiration can be gathered from other connections and other industries.

    - *Interpretation of the definition and the important requirements and criteria:* Try to make the important requirements and criteria, which are stressed in the definition, more concrete; what do the requirements mean in practice? In order to investigate how easy assembly could be divided into more concrete sub-criteria, *Connection design method* by Jürisoo and Staaf (2007) could be used. Investigate how the intended load path for the system affects the connections; which connection types are needed in order to take care of the loads? Information about the intended load path is needed.

- *Elimination of solutions:* On the basis of the definition and the intended load path; reject the misaimed connection devices. The unrealistic connections should as well be rejected.

- *Forming connection concepts:* Gather connection devices into connection concepts. A concept should be able to resist all loads that were stated in the *interpretation of the definition and the important requirement* sub-activity. Connection devices may be used in more than one connection concept.

- *Improvements of the concepts:* Improve the connection concepts with regard to the absolute and evaluable requirements.

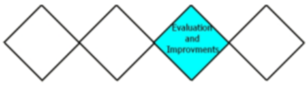
- *Comparison between the connection concepts and the evaluation criteria:* Do a more comprehensive judgement of each criterion for each connection concept.

- *Requirements on the system:* Decide what the system must fulfil if a particular connection device should be used. Communicate the requirements to the system development group by filling in the system requirement table (Table 6).

- *Control of the absolute requirements and system requirement check:* Calculate how big force magnitudes the connection devices can resist. Assure that requirements on the system are fulfilled (Table 6). Load magnitudes and judgement of the requirement on the system is needed from the system.

- *Concluding conceptual design:* Make sure that all decisions and tasks in the activity completion table (see Table 5) concerning conceptual design are fulfilled.

- It is important to emphasise that this activity is iterative; it is allowed to go backwards within the activity when a design is not sufficient.



Evaluation and improvements

The aim with this activity is to present one connection concept that should be delivered to the *detailed design* activity. The concept should be ready in such extent that the *detailed design* activity should give dimension and ranges for how the connections can be adopted in project development. This means that the concepts have to be evaluated and optimised in order to be able to select the most suitable concept. These two sub-activities may be repeated since iteration may be needed to be able to produce a connection concept that satisfies the aim with the activity.

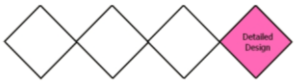
- Start the activity with a discussion concerning the different concepts and the definition. The conclusion should result in which criteria that should be evaluated.

- Decide how the aim with the activity should be reached, how should the connections be evaluated, which methods should be used etc. The evaluation methods should be more sophisticated the longer the activity reaches. For example, initially: simple drawings in combination with opinions from people with experience from design and assembly may be enough. Later in the activity a more sophisticated tool should be used. In order to evaluate easy assembly the evaluation tool in *Connection Design and Evaluation Method* (Jürisoo and Staaf, 2007) may be used.

- On the basis of the results from the evaluations try to improve the concepts in their problem areas.

- The evaluation methods should be more close to real life, e.g. virtual reality simulations, real life tests with the connection devices and full scale trials with elements included, when the concepts gets closer to their final design. Real life trials should be carried out in the latter stages of the activity and should work as an acknowledgement that the connection concept works as expected.

Detailed design



This activity aims to give the connection concept its final design and to state where and how the different connection devices should be used.

- State between which load magnitudes the different connections should be used.

- Implement the connections in different design systems for design of the different projects.

- Make the connection devices ready for manufacturing and project adaption

Case Study

In order to test the relevance in the earlier suggested guidelines for new development of connections it is necessary to simulate a case; how connection details in a building system should be developed on the basis of the method for connection design. The case study intends to describe how the development process will proceed if the guidelines, described in Chapter 6, are used. This case study is delimited to describe the content of the development process with regards to including activities and sub tasks that are directly linked to the connections. Other parameters that concern the development process such as group structure, time plan, organisation of meetings and risk analysis are not treated. Further on the system development's progress is considered to be carried out without any iteration though this might change the conditions for the connection development.

The connection details, a wall-to-floor, a wall-to-wall and a floor-to-floor connection, which the development process should result in, is described in Section 7.1 together with a system description. It is important to point out that the information presented in 7.1 is not known when the product development regarding connections is started. It is presented in order to give the reader an overview of the system when reading about the development process, which should ease the understanding of why certain choices are made.

In a real development process many solutions are invented, developed and rejected during the process until the optimal solution is found. This case study does, however, emphasise the process for the chosen connection. The connections that will be rejected during the process are only described briefly.

Building system description

The connection concept that is used in this case study is a part of a system, which is under development, by the company Consolis. Consolis is part of the European research project ManuBuild (see Section 1.1.3). The motive for the development of the system is to develop connections, in a concrete prefabrication system, which does not require complementary grouting. The incentive is to shorten construction time, since cast on-site contains time for hardening and an irrational assembly process.

All details and information about the building system are not known, since Consolis building system still is under development. The fact that all details and information are not known is not an essential issue for this case study since it aims to describe the development process with included activities and not the details in the system. Consolis building system is used as a tool to describe the process. Therefore, in order to be able to simulate the development process, unknown information about the system is assumed.

The load bearing elements, their details and intended structural behaviour are presented below. A principle sketch of a possible way to arrange the elements that are part of the building system is shown in Figure 11.

Figure 11 Principle sketch of Consolis building system, Consolis (2007).

Element descriptions

Intermediate floors: The floor-elements are made of pre-stressed concrete with bolted connections and are intended to work as one way slabs supported on load bearing walls (Figure 12). The floor elements also work as supports for wall elements (Figure 13), this restricts support rotation and the connection is considered to be partly fixed and a negative moment at the supports must be considered. Further on, the floor elements are part of the stabilising system, and function as diaphragms and are designed thereafter. The loads should be transferred between the floor elements by friction and by the connections themselves. The length of the floor elements can be freely chosen up to ten meters. The standard width is 2.4 meters. The thickness of the floor elements are set to 0.2 meters and load capacity is instead adjusted with reinforcement and degree of pre-stress. On top of the intermediate floor elements an internal floor is placed. The internal floor has room for installations; it is 15 cm thick and consists of light exposed aggregate and construction board on top.

Figure 12 Intermediate floor element supported on wall element, Consolis (2007).

Figure 13 Wall element supported on floor element, Consolis (2007).

Wall elements: There exists load bearing and non-load bearing walls both made of reinforced concrete with bolted connections. The thicknesses are 200 mm and 80 mm respectively. The wall elements are designed as sandwich type or joint free, when they are used as façades. The stability during assembly is solved by special elements in the corners (Figure 14).

The shear forces between the elements can be transferred, as for the floor elements, with friction or through the connections only. The height of the elements is set to three meters in order to permit space for installations and sound insulation etc. and an inner storey height of 2.85 meters. The maximum length of the wall elements is ten meters.

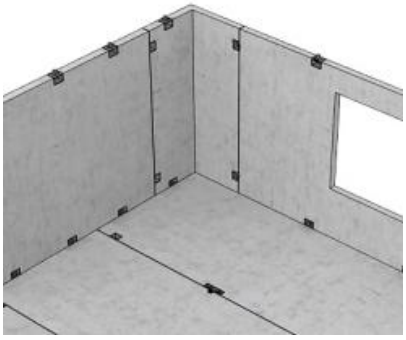


Figure 14 Special corner element, Consolis (2007).

Connection description

The main connection that is used in the building system can be used as floor-to-floor, floor-to-wall- and wall-to-wall connection. The connection devices, which are made of steel plates, are cast into the elements. The connection between the elements is solved by a bolt. A rubber sealing band should be placed between the elements in order to provide tightness. The rubber sealing should also transfer shear forces and compression forces. The connection devise is shown in Figure 15 when used in a floor-to-floor joint and in Figure 16 when used in floor-to- wall joints. To ease the assembly, without putting too big demands on tolerances when manufacturing the elements, the hole in one of the connection devices is made bigger then the bolt. The interaction between the bolt and the connection is solved by using a washer. To hide the devices in the walls a cover plate with the same colour as the wall is used. The floor elements are covered by an inner floor, which means that no further cover is needed where the connections are situated at the floor.

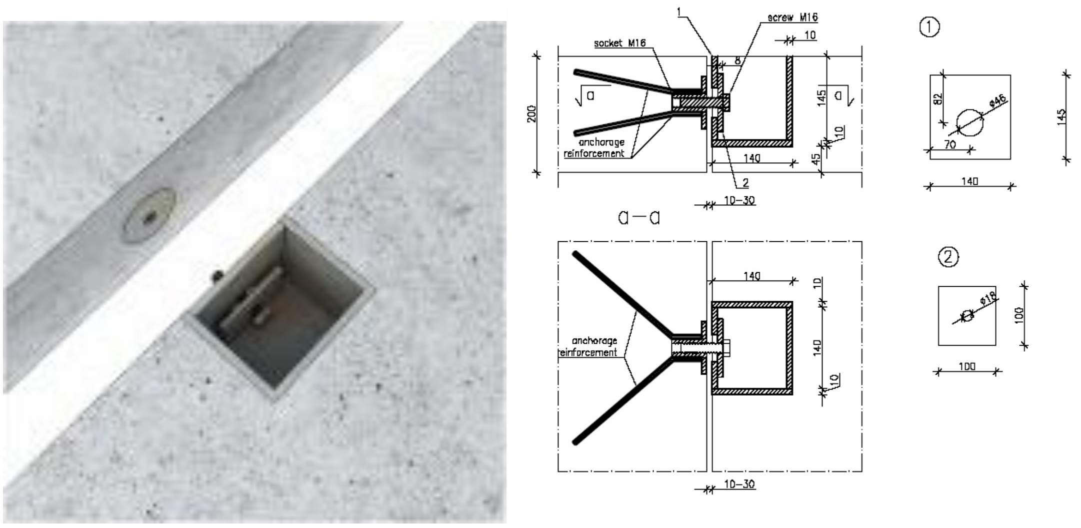


Figure 15 Bolted floor-to-floor connection, principle sketch and detailed drawing, Consolis (2007).

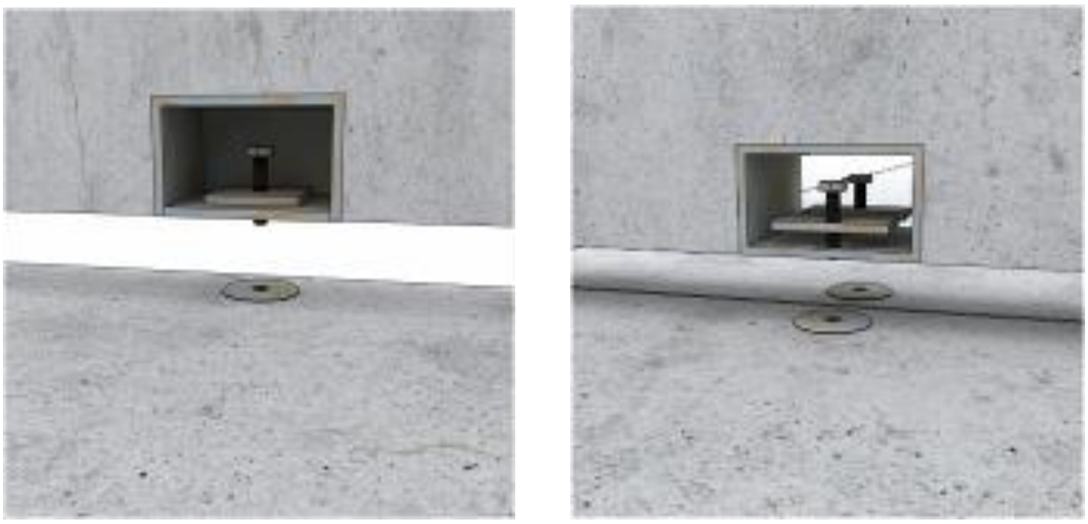


Figure 16 bolted wall to floor connection with one and two floor elements respectively, Consolis (2007).

In case of a high building an axial connection device must be used, in order to take care of the extra high shear forces. This connection devise works the same way as the original. The biggest difference is that a plate is used instead of a bolt to transfer the forces between the elements. The plate is bolted in both of the elements (see Figure 17).

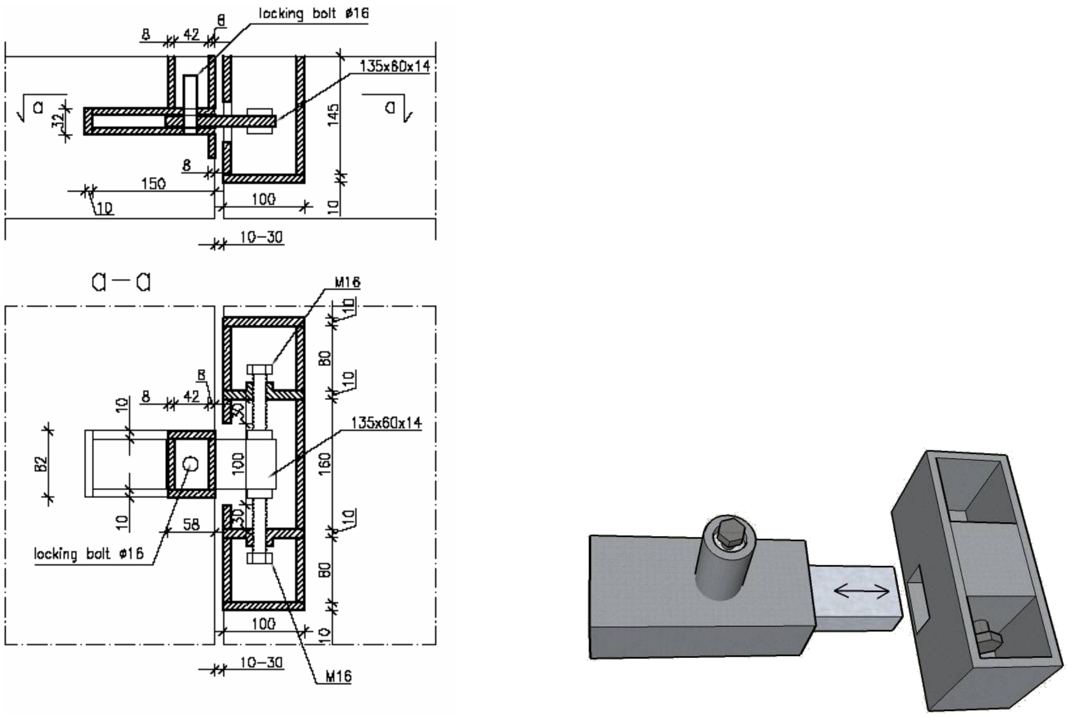


Figure 17 Detailed drawing and principle sketch of an axial connection, which is used in order to take care of large shear forces. (Consolis, 2007)

System definition – input necessary for connection development

As described above, a development process on system level precedes the connection development. In order to get a reasonable description of what the connection development process is based on, it is necessary to describe output from the preceding process. This chapter aims to describe what has been stated on system level from the system definition until the connection development is initialised.

The system is defined as follows.

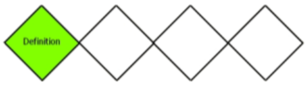
Project scope: Transportations within east of Europe, with a main focus in the vicinity of the factory.

Specifications of the target market: The houses that are built within the system are residential buildings and office buildings.

Product concept: The industrial process is emphasised in the building system, which results in high quality to a low cost. High flexibility should give the customer the opportunity to freely choose layout and aesthetics. The system should give priority to a high level of completeness to follow the industrial concept. The system should emphasise “sustainable development” thinking.

Product features, attributes and requirements: The number of stories is restricted to be less than eight, due to fire regulations. To be able to have a freedom to chose layout non load bearing partition walls are allowed in the system. Further on, the houses should keep a low profile in an architectural point of view, and they should not look like typical pre-fabricated houses with visible joints.

Connection definition



The first activity of the connection development is the definition. The activity contains a definition of the development process and a definition of the connection itself. This chapter follows the guidelines given earlier in this report. Parallel with this activity, activities that should result in other components, e.g. wall elements, goes on. It should be emphasised that the system definition has not prescribed any type of structural system yet. This means that several structural systems are investigated and hence several groups of connection concepts are handled, but not described.

Structure of the development process

The first thing to do, when the connection development starts, is to decide what the development process should contain.

A group is compound, with all necessary professions. When the group is formed, all aspects described in the guidelines are considered.

Four activities are stated; *Definition*, *Conceptual design, Evaluation and improvements* and finally *Detailed design*. A time schedule is set up, where it is decided when the activities should begin and end. Further on, the aim with each activity is stated as well. *Definition*: defining which affects the system's definition has on the connections. *Conceptual design*: Come up with a couple of concepts. *Evaluation and Improvements* select one concept. *Detailed design*: optimise and design the connection concept and make it ready for manufacturing.

It is decided that meetings should be held on weekly basis. In addition it is decided that all participants should keep a journal. They should also report there progression continuously to the project leader, who sets up a project report and delivers it to the whole group. All information should be treated through a web page, which is set up during this first activity.

Two documents are stated, where all requirement and criteria that effects the connection are set up; evaluation criteria (Table 7) and absolute requirements (Table 8). These tables will be further filled in during the development process. Assembly and load bearing capacity can be filled-in in this early stage since they are essential requirements and criteria.

Table 7 Evaluation criteria table concerning the connections, which should be further filled in during the process. Updates in the table are bold.

Nr	**Evaluation criteria:** Parameters:	Aim: The connection should…
E1	**Assembly**	**Allow a fast assembly of the elements**

Table 8 Requirement table for absolute requirements concerning the connections, which should be further filled in during the process. Updates in the table are bold.

Nr	**Absolute requirements** The connection should…	Fulfilled Yes/No
A 1	**Be able to resist all applied forces**	

An activity completion table is set up (Table 9), in which it is explained what decisions and tasks that have to be made in order to conclude an activity. An activity can be concluded when all tasks and decisions concerning that particular activity are made. The aim of each activity can be filled-in in the table. It is also decided that the structural system should be set before the conceptual design can be concluded.

Table 9 Activity completion table, an activity can be concluded when all sub-tasks or decision are made, i.e. when the boxes of interest are market yes. Updates in the table are bold.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	
1	**The stated activities should be confirmed**	**X**		
2	**The structural system should be set before the conceptual design can be concluded**	**X**		
2	Come up with a couple of connection concepts		X	
3	Select one concept.		X	
4	Optimise the connection and make it ready for manufacturing		X	

Connection definition

Investigations and research work based on the system definition have resulted in basic conditions on system level. The basic conditions that are directly of interest for the connection development are presented here:

Type of system: The load bearing system should contain planar elements, in order to make the product easy to transport and allow flexibility. Depending on how the structural system will be solved the demands on the connections will vary, e.g. pinned or fixed.

Level of flexibility: The building system should have a standard wall height, element thickness and element width; the remaining measurements should be adjustable. The fact that the fixed parameters of the elements are the floor height, the element thickness and the element width means that the load variation on the connections will be big.

Multi functionality: Optimisation is not crucial, components should rather be possible to use in many cases and settings than be optimised for a certain case. This in combination with the level of flexibility aspect means that the connections should be designed so they can be adopted in a lot of different settings and positions of the system. The design will therefore be on the basis of the worst case scenario.

Fast assembly: Fast assembly is crucial for the connections, since the industrialised process is emphasised in the system definition.

Level of completeness: The system definition emphasises a high level of completeness of the elements when they are assembled. This excludes jointing methods that could pollute the elements, such as grouting and welding. This coincides with the fast assembly demand since grouting and welding are time consuming activities.

Functionality: The houses should be adoptable to both residential and office buildings. To be able to create an enjoyable environment for the tenants extra demands on the connections occur. These demands are, for example, concerning tightness with respect to sound, air-leakage and heat.

Accessibility: Inspection and maintenance of the components should be possible.

Environmental aspects: Sustainable development is considered in the system definition and hence it should be possible to demount the houses, thus should the connections be demountable. To get a sustainable house it is preferable to have possibilities for inspections and maintenance of the connections, i.e. the accessibility aspect is important for environmental reasons as well.

Architectural aspects: The system should allow different architectural solutions and the fact that the houses are prefabricated should not be obvious. Visible joints should therefore be avoided. The design should allow freedom for different inner planning solutions.

Economical aspects: Since the system’s buildings should be as cheap as possible it is important to have a rational assembly process. Material prices and manufacturing methods are of course important but may have less importance than the assembly aspect. This since the connections are physically small relative the elements. Savings can of course be done with bigger quantities, which aligns with the multi functionality aspect.

These aspects from the system definition can be translated into a definition of the connections:

Connection definition

In addition to absolute requirement, like load bearing capacity, and function requirements, like tightness regarding air leakage, sound, heat and moisture the main focus in the connection design should be easy assembly. Other required features are: multi functionality, demountability and accessibility. Economical aspects should off course be considered in the development process. Fulfilling this connection definition, in as big extent as possible, is the aim of the development process.

The system is now interpreted and a connection definition is composed. The absolute and evaluation criteria are inserted in the tables (see Tables 10 and 11).

Table 10 Requirement table for absolute requirements concerning the connections. The table should be further filled in during the process. Updates in the table are bold.

Nr	**Absolute requirements** The connection should…	Fulfilled Yes/No
A 1	Be able to resist all applied forces and be designed according to valid codes and regulations	
A 2	**Not convey welding or grouting on site**	

Table 11 Evaluation criteria table concerning the connections. The table should be further filled in during the process. Updates in the table are bold.

Nr	**Evaluation criteria** Parameters:	Aim: The connection should…
E1	Assembly	Allow a fast assembly of the elements
E2	**Tightness**	**Be tight against leakage regarding, sound, air, moisture and heat.**
E3	**Multi functionality**	**Be able to use in many situations**
E4	**Demountability**	**Be easy to demount**
E5	**Accessibility**	**Be easy to access**
E6	**Economy**	**Be cheap**
E7	**Visibility**	**Not be clearly visible**

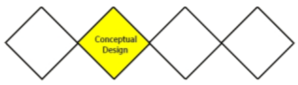
The connection definition, and the requirement and criteria tables, should give the connection development group a good starting point for conceptual design. It should be emphasised that the tables not are completed; every requirement and criterion should be divided into more specific sub-requirements or sub criteria. The lists are also going to be filled in with new requirements and criteria. The definition and the tables are approved by the system development group and the activity can therefore be concluded.

Further on, before the conceptual design can be initiated it is necessary to decide which system concepts that should be investigated. Every system concept corresponds to a connection development process and these processes proceeds parallel. This decision is inserted to the activity completion table (Table 12). The system development group decides that three different concepts should be investigated; load bearing concrete walls, steel frames with light walls and concrete walls with steel framing. All decisions and tasks concerning *activity 1* are made (see Table 12), and the activity can consequently be concluded.

Table 0.1 Activity completion table, an activity can be concluded when all sub tasks or decision are made, i.e. when the boxes of interest are ok. The table shows that activity 1 can be concluded. Updates in the table are bold.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	**Yes**
1	The stated activities should be confirmed	X		**Yes**
1	**It should be decided which system concepts that should be investigated**	**X**		**Yes**
2	Come up with a couple of connection concepts		X	
2	The structural system should be set before the conceptual design can be concluded	X		
3	Select one concept.		X	
4	Optimise the connection and make it ready for manufacturing		X	

Conceptual design



This activity's aim is to find a hand-full of promising solutions of how elements can be jointed together. It is important to have in mind that the conceptual design activity includes parallel development processes, as explained in Section 7.3.2. Each system concept, with the belonging connection, is treated as a unique development process. These concepts includes load bearing concrete wall and floor elements, steel frames with light walls and concrete walls with steel framing. However, this case study has been delimited to investigate only one of these concepts, concrete floor elements with load bearing concrete walls and the joining of these. This system concept involves a few different situations, wall-to-wall, floor-to-floor and floor-to-wall connections. In addition, it is different situations when, for example, walls should be connected with a horizontal or a vertical joint. Connection devices should of course be developed for all of these situations.

A planning of the *conceptual design's* sub-activities is made in this early stage of the activity. The planning includes which input and output to and from the system development group that is needed for the different sub-activities. The planning of the sub-activities is shown in (Table 13). The conceptual design activity is iterative and the procedure can go backwards if requirements or criteria are not fulfilled. The sub-activities in Table 13 are further described in the sections below7.4.1-7.4.9.

Table 13 Conceptual design is divided into sub-activities. The output and input that is needed for the different sub-activities are shown in the second column.

Sub-activity	**Output to or Input from the system**
Brainstorming	
Interpretation of the definition and the important requirements and criteria	Input: Intended load path
Elimination of solutions	
Forming connection concepts	
Improvements of the concepts	
Comparison between the connections and the evaluation criteria	
Requirement to the system	Output: Requirements on the system
Control of the absolute requirements and system requirement check	Input: Load magnitudes and judgement of the requirement on the system
Concluding conceptual design	Input: choice of five concepts

It is also decided that all connection devices that will go further to next activity, *Evaluation and improvements*, should fulfil the stressed evaluation criteria to a high degree and all of the absolute requirements. This is inserted to the activity completion table (Table 14).

Table 14 Activity completion table, an activity can be concluded when all sub-tasks or decisions are made, i.e. when the boxes of interest are ok. The table shows that three new tasks (bold) should be fulfilled in order to complete activity 2.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	Yes
1	The stated activities should be confirmed	X		Yes
1	It should be decided which system concepts that should be investigated	X		Yes
2	Come up with a couple of connection concepts		X	
2	The structural system should be set before the conceptual design can be concluded	X		
2	**The connections should fulfil the absolute requirements**		**X**	
2	**The connections should fulfil the stressed evaluation criteria to a big extent**	**X**	**X**	
2	**It should be confirmed that the requirement on the system are reasonable**	**X**		
3	Select one concept.		X	
4	Optimise the connection and make it ready for manufacturing		X	

Brainstorming

The connection development group starts with a brainstorming meeting and a discovering phase. The connections of interest in this system concept are floor-to-floor, floor-to-wall and wall-to-wall connections. The brainstorming phase does therefore concern all these connections. As a start for the conceptual design several non-detailed solutions on connections are sketched. In this stage the quantity is more important than the quality; solutions that may seem “crazy” are accepted in order to allow creativity. This brainstorming will of course generate solutions that not correspond to the connection definition and they can therefore easily be rejected. Others can be rejected since the solutions are not realistic to solve in practise. However, the idea with the brainstorming is to allow innovative thinking, which may lead to something totally new. If a standard connection, which has been used before, is most suitable after all it will be shown later in the process. The result of the brainstorming is visualised in Figure 18. Inspiration for these connection concepts has been gathered from existing connections as well as from other areas than building construction.

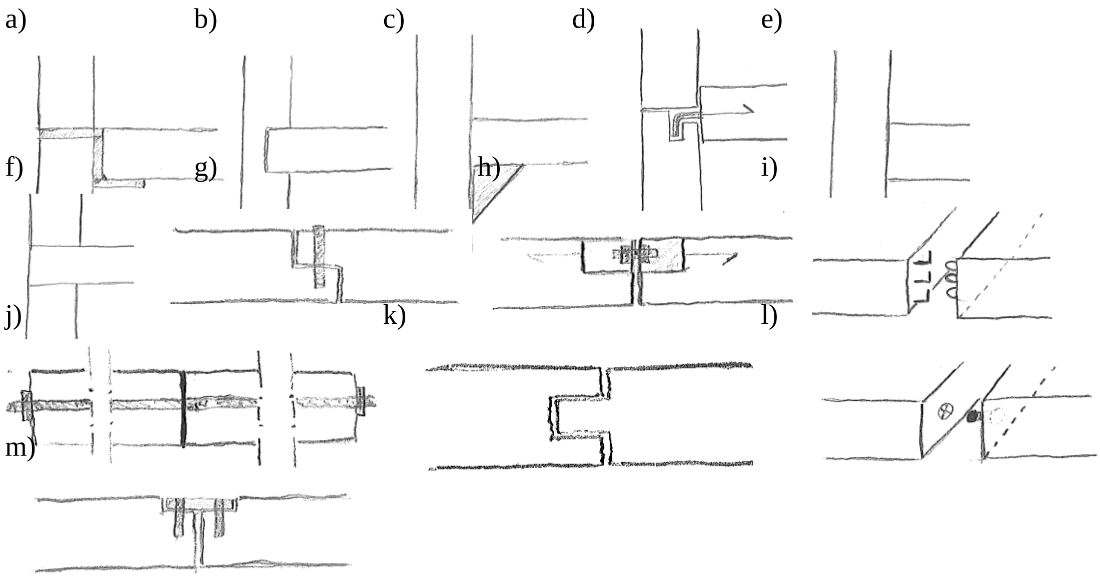


Figure 17 Connection devices invented in the brainstorming phase. a) z-profile b) Recess in element c) Cantilever support d) Hook e) Glue or Burdock f) Floor element between wall elements g)Bolted elements h) Screwed plates i) Hooked coils j) Post tensioned elements k) Recess in element l) Click connection m) Bolted steel plate.

Interpretation of the definition and the important evaluation criteria

The connections should, due to the definition, be easy to assemble. The connection development group does therefore check which criteria that has to be considered for a connection design that is easy to assembly. Jürisoo and Staaf (2007) have developed a method for how to design for easy assemble. The method contains sixteen criteria that should be evaluated. The criteria are presented in Table 15. The table functions as an appendix to the assembly criterion in the evaluation criteria table (Table 15).

Table 15 Criteria that should be considered in design for easy assembly, Jürisoo and Staaf (2007). See Appendix A.

1a	Stability	Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.
1b	Positioning of Elements	Elements should preferably be guided into their final position.
1c	Positioning of Loose Parts	Loose connection details are preferred to be self guiding
1d	Number of Loose Parts	The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part
1f	Size of Loose Parts	Long or wide loose parts that are hard to handle should be avoided.
1g	Weight of Loose Parts	Heavy loose parts should be avoided.
1h	Need for Assembly Workers	The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.
1i	Safety for Workers	The risk for workers getting injured in the assembly process because of the connection should be minimized.
1j	Tools	Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.
1k	Accessibility	Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.
1l	Fixation Method	Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.
1 m	Protruding Parts	It is important that connections are not fragile or harmful to components, protruding parts, other connections and personnel.

1n	Multi-Purpose Connections	Try to integrate lifting devices in the connection. The elements should hang straight when lifted.
1o	Fool Proof	It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.
1p	Demountability	Elements should be possible to demount without getting damaged.
1q	Tolerance	Connections that are easy to adjust regarding tolerances are preferred.

In addition to the assembly criterion the system development group has come up with a concept concerning the intended load paths. This is of interest for the absolute requirement, load resistance, and should as well be considered in the initial evaluation of the connection concepts.

The intended load paths are delivered in sketches from the system development group and are presented in Figures 19 and 20. Figure 19 shows the vertical load path. The floor-to-wall connection can be pinned or fixed. A fixed end connection sets more requirements on the connection. On the other hand, a fixed end connection allows larger span. It is decided that designing the connection as a fix end is too difficult since grouting is not allowed. Therefore, the connection should be designed as pinned. Furthermore, it is necessary to have interaction between the floor elements to assure that the floor elements function together as a slab element. Otherwise, one element can not spread the load to the adjoining elements and as a result local deflections may be too large if an element is subjected to a point load for example. This demands the connections to transfer shear forces in the vertical direction. Two approaches are found out, either by transferring the shear through the connections only or by using the connection to assure that friction between the elements can transfer the shear.

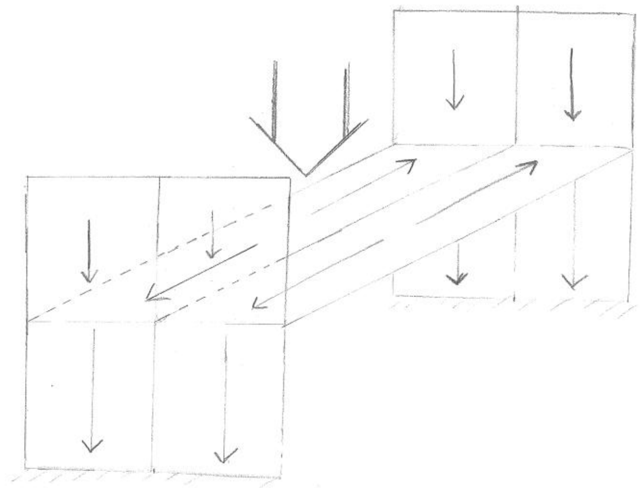
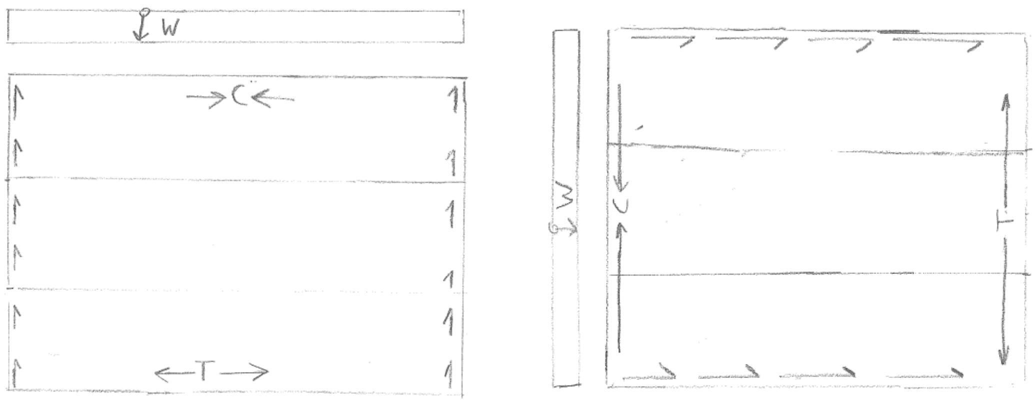


Figure 19 Principle sketch of how vertical loads are transferred to the foundation.

To stabilise the system two approaches are found. The first one is to take moment in the wall/floor connections, i.e. by the use of frame action. The moment forces are, however, going to be too large since the lever arm in an eight story building is about 24 meters, which is considered to be too much. The other approach is to transfer the horizontal forces to the walls that are going to function as shear walls. This does, however first of all demand the floor to work as a deep beam, which means that the connections should be able to take shear forces. This is, however, a demand that is already set due to the interaction between the elements, but in this case the shear flow is in the horizontal direction. More over, the connections must be able to transfer the loads to the walls with shear forces. Tension and compression forces occur since the floor works as a deep beam (Figure 20), which of course has to be considered.

In the load case that Figure 20 a) shows that the tension and the compression zones are in the length direction of the slab, which sets no requirements on the connections. The other load case is illustrated in Figure 20 b) where the tension and the compression forces are transferred between the elements. This demands that the connections should be able to transfer these forces.



a) b)

Figure 20 Principle sketch of force flow due to wind load, a) wind perpendicular to the floor elements and b) wind parallel to the floor elements.

The horizontal forces, should as mentioned above, be transferred from the floor elements to the wall elements that transfer them down to the foundation. This way of transferring the load can be explained as cantilever action, where many interacting wall elements are forming a cantilever beam. This cantilever action is illustrated in Figure 21.

When the walls are functioning as shear walls, tension and compression in the horizontal joints must be considered (Figure 21). Compression is not a real problem since the walls are made of concrete, which is very resistant to compression. The connections support area must however be of a certain size to avoid stress concentrations when compression is transferred into an element, i.e. disturbed regions must be considered. Vertical shear forces between the elements must also be considered in order to use the total width of the wall elements as the depth of the cantilever beam. All of these requirements are compiled in the absolute requirement table where the force types are specified (Table 16).

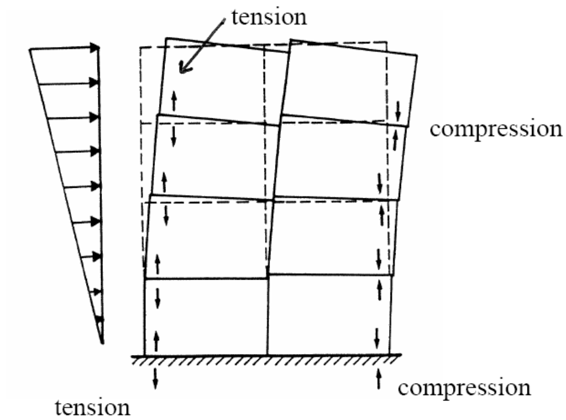


Figure 21 Principle sketch of force flow due to wind load, cantilever action, Fib (2007).

Table 16 Absolute requirement table concerning the connections. The table should be further filled in during the process. Updates in the table are bold.

Nr	**Absolute requirements** The connection should…	Fullfilled Yes/No
A1	Be able to resist all applied forces and be designed according to valid codes and regulations	
A1a	**Resist shear forces between floor and wall elements, i.e. between deep beam and shear wall, arisen from wind loads**	
A1b	**Lifting forces, between wall/wall or wall/floor depending on the connection design**	
A1c	**Compression forces between wall/wall or wall/floor depending on the connection design**	
A1d	**Resist shear forces between floor elements that transfers wind loads to the shear walls, between elements that are part of the deep beam**	
A1e	**Tension force between floor elements that are part of the deep beam. Assuming that the connections functions as flanges of the deep beam**	
A1f	**Compression force between floor elements that are part of the deep beam. Assuming that The connections functions as flanges of the deep beam**	
A1g	**Vertical shear force between wall elements**	
A2	Not convey welding or grouting on site	

Elimination of solutions

On the basis of the criteria from the assembly method and from the absolute demands gained from the intended structural function the connection development group can easily reject a couple of solutions. After this elimination the connection development group has a couple of promising solutions left that can, or will after some changes, be able to fulfil the criteria and the absolute demands. The remaining connection details are shown in Figure 22.

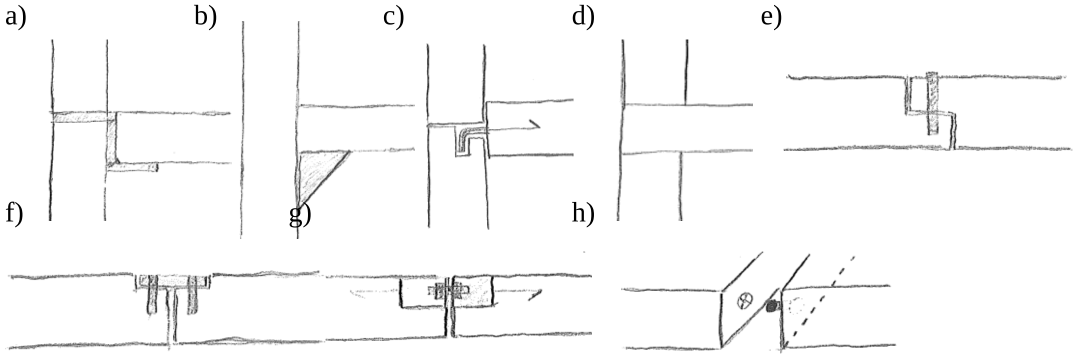
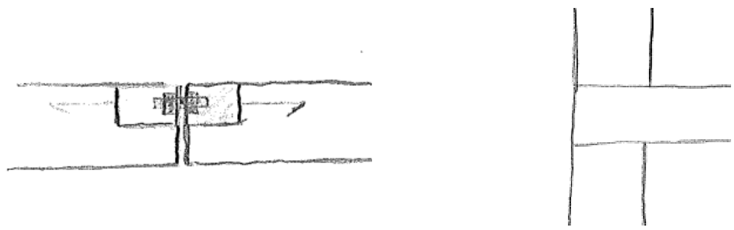


Figure 22 *Connection concepts invented in the brainstorming phase and that are not rejected in the first elimination. a) z-profile b) Cantilever support c) Hook d) Floor element between wall elements e) Bolted elements f) Bolted steel plate g)Screwed steel plates h) Click connection*

Forming connection concepts

Connection devices are gathered into connection concepts, which is able to resist all load situations in the absolute requirement table (Table 16). Several concepts are formed but only one is described in this case study. It should be mentioned that the devices can be used in several concepts. The chosen devices that form the concept are shown in Figure 23. The bolted steel plate (Figure 23 a) is intended to be used between floor elements and between wall elements in vertical joints. A combination of the two connections in Figure 23 is going to be used as wall-to floor connection.



a) b)

Figure 23 *Concepts that should be further developed a) Bolted steel plate b) Floor element between wall elements.*

Improvements of the concepts

On the basis of the absolute requirements and evaluation criteria each connection concept has to be improved. This section describes how one connection concept is developed; the connections, which where invented in the brainstorming phase, are shown in Figure 23. Other solutions are further developed as well, but the development of these concepts is not explained in this case study. The connection between floor and wall (Figure b) must be improved in order to resist all loads. The idea is to have a similar solution as between wall elements and floor elements. The connection device in Figure 23 a) can be directly implemented to both the floor-to-floor situation and to the wall-to-wall situation where the joint is in vertical direction. A device suited as a wall-to-floor connection can be developed if the two connection device concepts in Figure 23 are combined. The improved connection devices are shown in Figures 24 and 25. The connections can be considered as multifunctional since the same principles are used in both devices.

The modification of the floor-to-wall connection is, as shown in Figure 25, made by replacing one of the connection devices with a cast in nut. These connections' structural function is able to resist all forces in the absolute requirement table (Table 16). The magnitude of the forces is however not considered yet. It is therefore necessary to do investigation about force magnitudes.

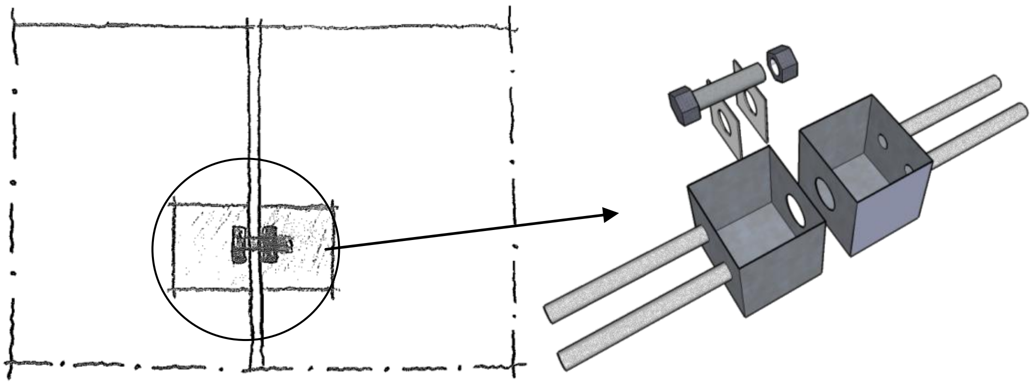


Figure 24 Sketch of floor-to-floor/ wall-to-wall connection. Visualised when cast in and the device only.

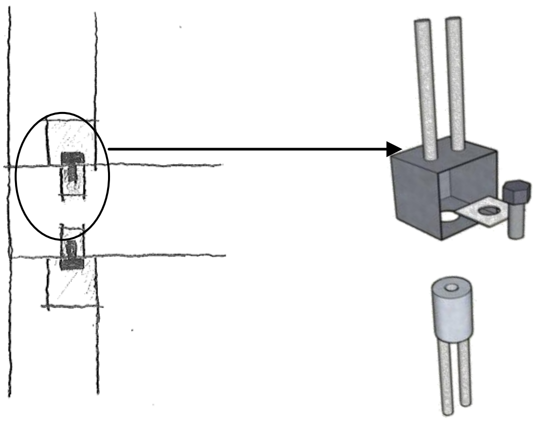


Figure 25 Sketch of floor-to-wall connection. Visualised when cast in and the device only.

Comparison between the connections and the evaluation criteria

The connection devices in Figure and Figure are now developed more detailed. The two devices are together considered as a connection concept. It is now time to check in which extent the connection devices fulfil the evaluation criteria.

Criterion 1, easy assembly is divided into several sub criteria, which is presented in an appendix (Table 15) to the evaluation criteria table (Table 16). The connection development group's opinion is that three sub criteria can be problematic in the continuing development concerning this connection concept, E1a) *Stability*, E1b) *Positioning of Elements* and E1p) *Tolerance*. The elements cannot surely be considered as stable and must therefore be provided with complementary bracings. The connection development group has, however, a suggestion that special corner elements can be used in order to provide stability and exclude superfluous work. *Positioning of elements* is also considered as hard to provide with the two connection devices. Wall elements get a clear guidance with help of, the earlier mentioned, special corner element. This method should ease the assembly. *Tolerance* is also a criterion that must be considered with extra caution in the continuing development. The connection can, however, provide some decreased demands on tolerances, since the washer allows bigger diameter of the hole than of the bolt, see Figures 24 and 25. It is still hard to handle problems with progressive deviations caused by imprecise element dimensions.

Multi functionality is fulfilled since only two devices are used and both use the same principles. *Tightness* must be provided with supplementary work. *Accessibility* and *Demountability* are fulfilled if the connections are not going to be covered with for example an interior floor. *Economy* is mostly connected to easy assembly. *Visibility*: the connection must be covered in order to be invisible. The comments about the different criteria are written in the evaluation criteria table (Table 17).

Table 17 Evaluation criteria table concerning the connections. The table should be further filled in during the process. Updates in the table are bold.

Nr	**Evaluation criteria** Parameters:	Aim: The connection should…	**Comments**
E1	Assembly	Allow a fast assembly of the elements	**Special corner elements are beneficial concerning 1a) and 1b). 1c) Tolerances must be considered. See appendix,** Fel! Ogiltigt resultat för tabell.
E2	Tightness	Be tight against leakage regarding, sound, air, moisture and heat	**Supplementary work**
E3	Multi functionality	Be able to use in many situations	**Fulfilled**
E4	Demountability	Be easy to demount	**Fulfilled if not covered**
E5	Accessibility	Be easy to access	**Fulfilled if not covered**
E6	Economy	Be cheap	**Connected to easy assembly**
E7	Visibility	Not be clearly visible	**Provided by a complementary cover**

Requirement to the system

The connection devices are now analysed with regard to the different requirements and criteria. In order to be able to use the connections requirements on the system have to be set. Some of the requirements are discussed in Section 7.4.5. The connection development group can therefore set requirement on the system.

First of all, the wall element is considered to be pinned, but the floor element is restrained to rotate since it is fixated between the two wall elements. Hence, a negative moment at the supports occurs and the floor elements must consequently be reinforced in the top at the end.

Since the connections are discrete an additional insulation along the elements is needed. This extra tightness requires supplementary work.

The cast in devices has also to be anchored in the concrete walls. This issue has to be considered of load transfer reasons and of manufacturing reasons. The steel plate surface should be in the same level as the element surface in order to avoid that compression forces will be transferred into the elements on a small area, i.e. the compression forces should be uniformly distributed along the element edge. This demands the elements to be fine and plain, which is tolerance and manufacturing requirements.

Further on, the connection types demand the element manufacturer and the manufacturer of the connection devices to have tight tolerances. The width and length of an element must be very exact. The connection can be designed in order to take care of small deviations by itself in order to make the element possible to assemble. Progressive deviations may be difficult to take care of, and tight tolerances are therefore demanded for the elements. High precision on the mounting of the devices in the elements is also demanded since the connection devices are going to be cast in the element.

The connection cannot assure stability during the erection, the walls must therefore be stabilised with help of additional bracings. This is unbeneficial with regard to assembly time. Another approach, which is better in an assembly point of view, is to have corner elements that are self stabilising, which the adjoining elements can stabilize against.

These requirements are delivered to the system development group with help of Table 18.

Table 18 System requirements set by the connection development group.

Nr	**System Requirements**
S1	The floor elements should be reinforced in the top at the supports
S2	Supplementary work for tightness
S3	Tight tolerances of element- width and length
S4	Anchoring of the devices must be considered
S5	Assure stability with help of special elements or bracings
S6	The elements surface must be fine to assure that compression forces can be resisted uniformly over an element
S7	The connections must be covered after assembly

Control of the absolute requirements and system requirement check

This stage of the conceptual design aims to check if the different concepts have potential to be used in the system. It is therefore time to assure that the absolute requirements can be properly fulfilled. Three results are possible after this stage; rejection, improvement or approval. If a connection concept is rejected it has no potential to fulfil the absolute requirements or it sets too hard requirements on the system. Improvement means that the connection has potential but must be improved. Approval means, of course, that the connection can go on to the next stage in the conceptual design.

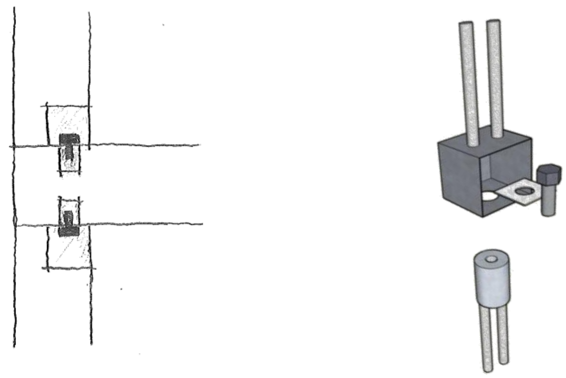
Since the connections should be designed according to worst case scenario, with consideration of the building system restrictions such as maximum building height and width, the largest magnitudes of load in each specific connection situation is delivered. The design loads are presented inTable 19. It should be emphasised that the load magnitudes in this case study are assumed.

Table 19 Requirement table for absolute requirements concerning the connections. The table should be further filled in during the process. Updates in the table are bold. All loads are assumed in this table.

Nr	**Absolute requirements** The connection should…	**Load Magnitude**	Fullfilled Yes/No
A1	Be able to resist all applied forces and be designed according to valid codes and regulations		
A1a	Resist shear forces between floor and wall elements, i.e. between deep beam and shear wall, arisen from wind loads	**775 kN**	
A1b	Lifting forces, between wall/wall or wall/floor depending on the connection design	**10 kN**	
A1c	Compression forces between wall/wall or wall/floor depending on the connection design	**20 kN**	
A1d	Resist shear forces between floor elements that transfers wind loads to the shear walls, between elements that are part of the deep beam	**775 kN**	
A1e	Tension force between floor elements that are part of the deep beam. Assuming that the connections functions as flanges of the deep beam	**48,5 kN**	
A1f	Compression force between floor elements that are part of the deep beam. Assuming that the connections functions as flanges of the deep beam	**48,5 kN**	
A1g	Vertical shear force between wall elements.	**100 kN**	
A2	Not convey welding or grouting on site		

Each requirement is investigated in order to see if the connections can withstand the load magnitudes. Rough dimensions of the connections are consequently stated. All calculations are based on worst case scenario.

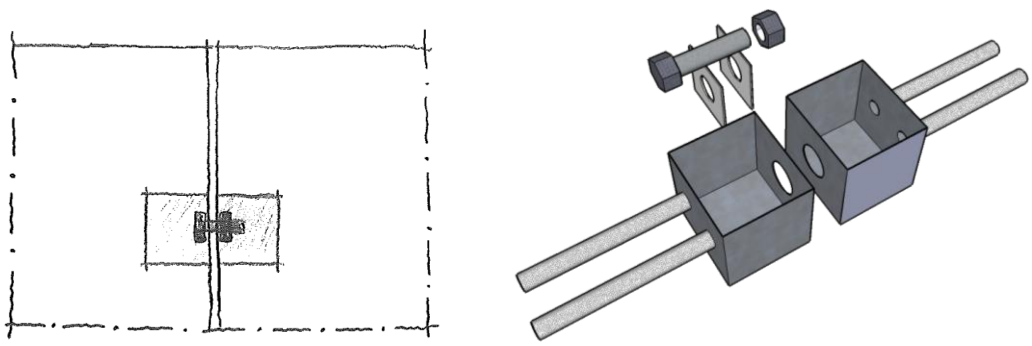
Requirement A1a demands that the joint between the floor and wall element can resist shear forces. The connection type between floor and wall is shown in Figure 26. Calculations show that one connection device with help of friction between the elements and shear resistance in the dowel can withstand the load magnitude. In order to have perfect interaction a rubber sealing band is going to be attached to the elements. The calculations are based on following connection dimension; 10 mm plate thickness and 16 mm bolt diameter. Requirement A1b and A1c concern the same connection. The connection development group has already set a demand that the elements should be plain. The system has confirmed that the rubber sealing band, which is used to provide interaction between the elements, can be used in order to transfer compression forces as well. This means that the connection devices do not have to take care of the compression forces, the support area on the wall element is large enough. The lifting forces must though be transferred through the connection devices. To resist these tension forces a bolt diameter of 16 mm it is sufficient, i.e. the same connection dimension as in the shear force case is sufficient.



a) b)

Figure 26 Connection device between floor and wall.

Requirement A1d demands that the joint between floor and floor can resist shear forces. The connection type is shown in Figure 27. Since this joint is in the horizontal direction, the deadweight from the floor elements will not help to assure friction even though the rubber sealing band is used. The connection must therefore assure friction between the elements by themselves or be improved, so that the connection itself can transfer greater shear forces. The forces are, however, too big and the connection device must be redesigned or changed.



a) b)

Figure 27 Connection device between floor elements and between wall elements vertical joint.

Requirement A1e treats the tension forces between the floor elements. The connection that will be used in this situation is shown in Figure . The connection will withstand the tension force with a bolt diameter of 16 mm and a plate thickness of 10 mm. To transfer the tension into the concrete element two reinforcement bars with a diameter of 16 mm are welded to the connection, see Figure 27. Requirement A1f demands the connection to withstand compression forces. The forces will be transferred through the rubber sealing band. The compression force will consequently be spread out over a bigger surface and the connections' function will be to assure contact between the elements. The compression forces can otherwise be transferred in the wall that is not intended to transfer compression forces. The floor element can transfer these compression forces. Requirement A1g concerns the same connection device, but in this case it is placed in the wall elements. The connection assures interaction between the elements together with the rubber sealing band, which means that shear can be transferred by friction.

After this check of the absolute requirements it can be concluded that all absolute requirement, except shear force between floor elements, can be solved by the two connection devices. It is therefore decided that a development of a special shear force connection should be initialised.

The system development group has received the requirement on the system, interpreted them and can therefore deliver an assessment of the requirements (Table 20). The system development group's opinion is that the requirements are reasonable. They do however consider that *the tolerances* can be a problem since concrete elements subjected to drying shrinkage. The result of the further development should show if the tolerances can be solved. More over, the system development group should investigate if special corner elements are a convenient method and if the method fits the system.

Table 20 System requirements set by the connection development group. Updates in the table are bold.

Nr	System Requirements	Comment from system development group
S1	The floor elements should be reinforced in the top at the supports	**Ok**
S2	Supplementary work for tightness	**Solved by an additional rubber sealing band**
S3	Tight tolerances of element- width and length	**May be a problem**
S4	Anchoring of the devices must be considered	**Ok**
S5	Assure stability with help of special elements or bracings	**Special corner elements should be considered in the system development.**
S6	The elements surface must be fine to assure that compression forces can be resisted uniformly over an element	**Provided by a additional rubber sealing band**
S7	The connections must be covered after assembly	**Ok**

Shear Force Connection Device – Iteration of Conceptual Design

This section has described that the shear forces between the floor elements where to large. It is therefore decided that the connection device should be improved. Since the process within the conceptual design activity is iterative the process starts over again. The connection devices that can transfer the forces they are subjected to must not go through the process again. It is the floor-to-floor connection that should be improved. It should be emphasised that the existing floor-to-floor connection still can be used in cases where the force is not that large and the same device is used in vertical wall-to-wall joints. Since the process in conceptual design is already described in this case study the new shear force device is presented without a presentation of the development process.

The shear force connection device consists of a steel plate that is connected to both floor elements. Before assembly the steel plate is stuck in one of the elements. When the elements are in right position the steel plate is inserted to the other one and it is then fixed to its correct position. A sketch of the shear force connection devices is shown in Figure 28

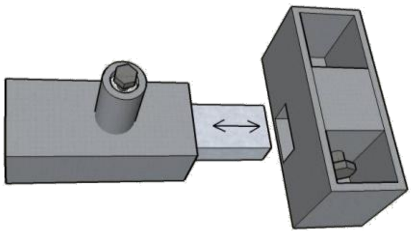


Figure 28 Connection device between floor elements, designed in order to resist big shear forces.

This connection device is only going to be used in case of a very high building, where the shear forces are big. The original connection is still used in the most cases in order to keep multi functionality criterion. The original connection is also considered as easier to assemble. The introduction of the shear force connection device conveys that all absolute requirements are fulfilled.

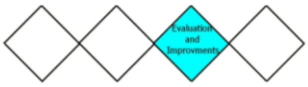
Concluding conceptual design

Before the activity is concluded the system development group checks the activity completion table. Five tasks or decisions should be made before the activity can be concluded. All of them are made and, hence the activity can be concluded. Five connection concepts are developed; all of them fulfil the absolute requirements and the stressed part of the evaluation criteria to a high degree. The system development group has confirmed that the requirements on the system, from all of the connection concepts, are reasonable. The system development group has also decided that the structural system should contain load bearing and stabilizing concrete walls and load bearing concrete floor elements. The activity completion table (Table 21) is therefore filled in.

Table 21 Activity completion table, an activity can be concluded when all sub tasks or decision are made, i.e. when the boxes of interest are ok. The table shows that activity 2 can be concluded. The updates in the table are bold.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	Yes
1	The stated activities should be confirmed	X		Yes
1	It should be decided which system concepts that should be investigated	X		Yes
2	Come up with a couple of connection concepts		X	**Yes**
2	The structural system should be set before the conceptual design can be concluded	X		**Yes**
2	The connections should fulfil the absolute requirements		X	**Yes**
2	The connections should fulfil the stressed evaluation criteria to a big extent	X	X	**Yes**
2	It should be confirmed that the requirement on the system are reasonable	X		**Yes**
3	Select one concept.		X	
4	Optimise the connection and make it ready for manufacturing		X	

Evaluation and improvements



The system development group has now decided that the structural system should contain concrete elements. The conceptual solution activity resulted in five concepts of connections for concrete elements. The connection development group should now evaluate these connection concepts and choose the most suitable one. All concepts fulfil the absolute requirements, and hence these requirements should not be considered in this activity. It is decided that the connections should be tested in real life before it is sent further to the next activity. This is inserted into the activity completion table (Table 22).

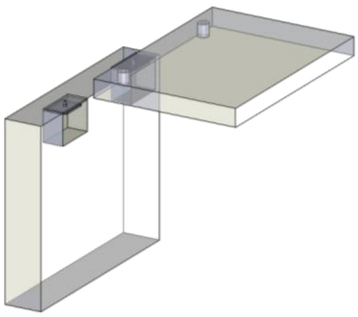
Table 22 Activity completion table, an activity can be concluded when the all sub tasks or decision are made, i.e. when the boxes of interest are ok. A new task concerning activity 3 is inserted (bold).

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	Yes
1	The stated activities should be confirmed	X		Yes
1	It should be decided which system concepts that should be investigated	X		Yes
2	Come up with a couple of connection concepts		X	Yes
2	The structural system should be set before the conceptual design can be concluded	X		Yes
2	The connections should fulfil the absolute requirements		X	Yes
2	The connections should fulfil the stressed evaluation criteria to a big extent	X	X	Yes
2	It should be confirmed that the requirement on the system are reasonable	X		Yes
3	Select one concept.		X	
3	**A real life test should be performed**	**X**	**X**	
4	Optimise the connection and make it ready for manufacturing		X	

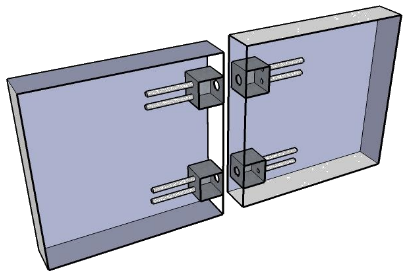
The evaluated connection concepts

This case study describes the evaluation of two of the five connection concepts, the procedure is, however, not different when more concepts should be evaluated. The first one (*connection concept 1*), whose development was described above, is shown in Figure 29. The second one is a developed z-profile connection (Figure 31), whose first sketch was presented earlier in this report. The z-profile connection (*connection concept 2*) has been developed in the same manner as *connection concept 1*. Both concepts contain the same connection devices in the floor-to-floor joint and in the vertical wall-to-wall joint. All included devices in the two concepts are presented in Figures 30 and 32 respectively. The evaluation is carried out for one connection device at the time. The floor-to-wall connection device is evaluated for both concepts in order to decide which of the two concepts that is best suited in the building system. Since the two concepts contain the same wall-to-wall/floor-to-floor connection device, the evaluation of this device is not decisive for the choice of concept. Instead the aim of the evaluation is to identify areas that could be improved.

Connection concept 1



a)



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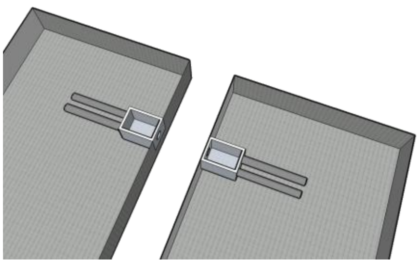
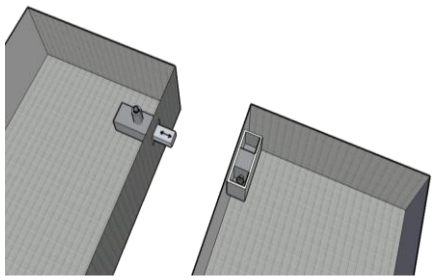
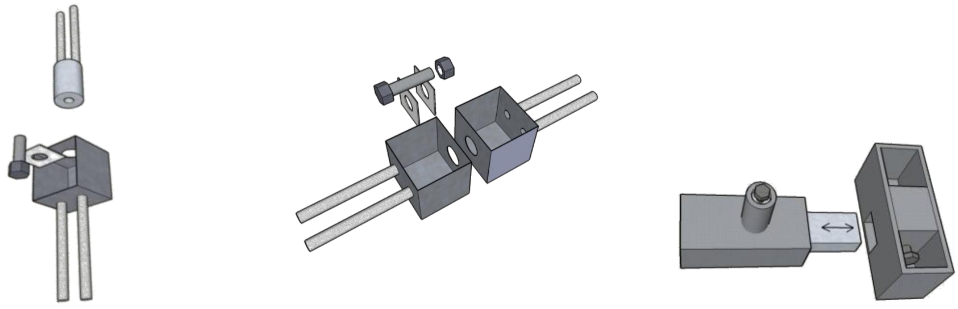


c)



d)

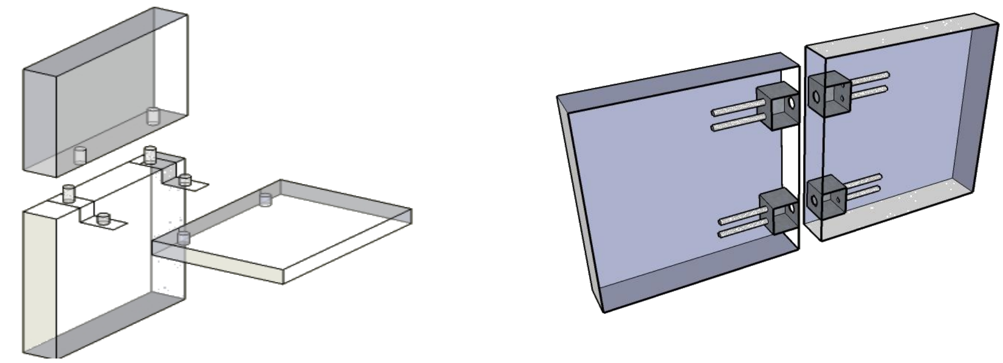
Figure 29 Connection concept 1 a) wall-to-floor b) wall-to-wall c) floor-to-floor d) floor-to-floor, in case of big shear forces.



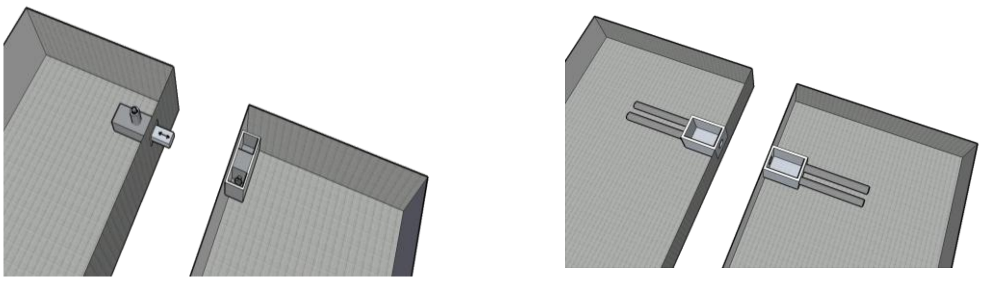
a) b) c)

Figure 30 Including connection devices: a) wall-to-floor, b) wall-to-wall/ floor-to-floor and c) floor-to-floor device in case of big shear forces.

Connection concept 2

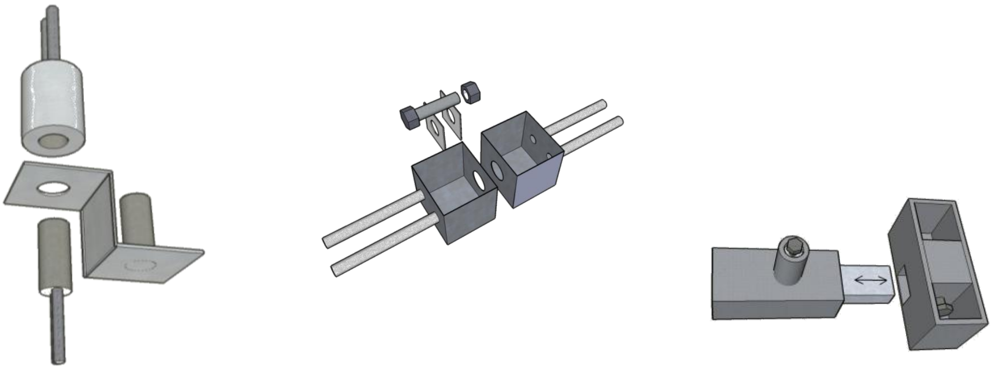


a) b)



c) d)

Figure 31 Connection concept 2 a) wall-to-floor b) wall-to-wall c) floor-to-floor d) floor-to-floor, in case of big shear forces



a) b) c)

Figure 32 Including connection devices: a) wall-to-floor, b) wall-to-wall/ floor-to-floor and c) floor-to-floor device in case of big shear forces.

Comparison of wall to floor connection devices

The first thing for the development group to do is to estimate what the evaluation criteria mean for each connection and to do a brief comparison. The criteria are presented in Table 23. The comments concern *connection concept 1* only. The comments that concerns *connection concept 2* are not shown. But a similar table exists and the differences between the two concepts are explained below. The connections of interest are shown in Figure 29 a) and Figure 31 a).

Table 23 Evaluation criteria table concerning connection Concept 1.

Nr	**Evaluation criteria** Parameters:	Aim: The connection should…	Comments
E1	Assembly	Allow a fast assembly of the elements	Special corner elements are beneficial concerning 1a) and 1b). 1c) Tolerances must be considered. See appendix, (**Fel! Ogiltigt resultat för tabell.**)
E2	Tightness	Be tight against leakage regarding, sound, air, moisture and heat.	Supplementary work
E3	Multi functionality	Be able to use in many situations	Fulfilled
E4	Demountability	Be easy to demount	Fulfilled if not covered

E5	Accessibility	Be easy to access	Fulfilled if not covered
E6	Economy	Be cheap	Connected to easy assembly
E7	Visibility	Not be clearly visible	Provided by supplementary cover

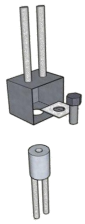
The most difficult criterion to evaluate is assembly. Evaluation of a connection concerning *Easy Assembly* requires a sophisticated method, and the connection devices are therefore evaluated with help of a *Connection Design and Evaluation Method* developed by Jürisoo and Staaf (2007). The easy assembly criteria that should be evaluated are presented in Table 15. The *Multi functionality* criterion can easily be judged since both the floor-to-wall devices are customised for the floor to wall joint. The *Multi Functionality* criterion can hence, not be considered as fulfilled. Both connection devices can be designed according to the worst case scenario, and hence they do not have to be compared further with regard to this criterion. *Tightness* in the joints should be provided with help of supplementary work and should therefore not be considered. The tightness in the connection itself must however be considered. Both connections are possible to *demount*, but the devices are going to be covered by an interior floor. The *accessibility* is therefore prevented and maintenance and inspections are therefore hard to perform. The connections are, however, placed in an indoor climate and are not exposed to any hazardous conditions. In worst case, if the connections are damaged, it is possible to access the connections if interior work is demolished. It is however positive aspects too, that the connections are no too easy to access. A person that does not have the right qualifications should not be able to access a connection. Economy is mostly decided due to the connections' ability to ease the assembly process. It is estimated that the z-profile is cheaper, since it is a standard profile, concerning the price for manufacturing the connection devices themselves.

This means that the connections are quite similar in most of the aspects. Differences exist in the multi functionality and economy criteria. In addition *Easy Assembly* should be further evaluated.

Evaluation of easy assembly for floor-to-wall connection devices

The assembly criterion is not properly investigated yet and since assembly is emphasised in the definition it is likely that this criterion is decisive. The connection development group makes a judgement of the assemblability with help of *Connection Design and Evaluation Method*. The floor-to-wall connection devices are initially evaluated. The evaluation is mainly performed in order to find the most suitable connection device but also to see in which areas improvements can be made.

Table 24 Evaluation between the two wall-to-floor connection devices, given by Jürisoo and Staaf (2007) and later in this report.

	Device 1				Device 2		
	NUMBER OF CRITERIA USED	15			NUMBER OF CRITERIA USED	15	
	MEAN GRADE	1,87			MEAN GRADE	1,61	
	INDEX	72%			INDEX	65%	
Criteria	**Importance**	**Point**	**Grade**		**Importance**	**Point**	**Grade**
Stability	0	-	-		0	-	-
Positioning of Elements	1	-1	-1		1	3	3
Positioning of Loose Parts	1	-1	-1		1	3	3
Number of Loose Parts	2	1	2		2	3	6
Size of Loose Parts	1	3	3		1	1	1
Weight of Loose Parts	1	3	3		1	-1	-1
Need for Assembly Workers	2	3	6		2	3	6
Safety for Workers	1	1	1		1	1	1
Tools	2	3	6		2	3	6
Accessibility	1	3	3		1	3	3
Fixation Method	2	1	2		2	3	6
Protruding Parts	2	3	6		2	-1	-2
Multi-Purpose Connections	2	1	2		2	-1	-2
Fool Proof	1	3	3		1	3	3
Demountability	2	3	6		2	3	6
Tolerance	2	1	2		2	-1	-2

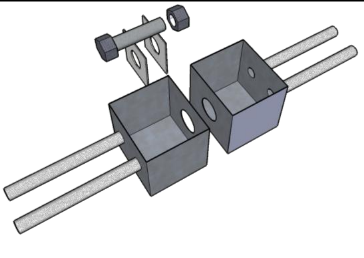
The evaluation shows that the two connection devices are quite similar with respect to easy assembly index. The cast in steel connection have, however, a better index, which indicates that it is a little bit easier to assemble. The z-profile (*Connection concept 2*) will therefore be rejected. The floor to wall device in *Connection concept 1* has two obvious problem areas where the grades from the evaluation are low; the positioning of elements and the positioning of loose parts criteria. The importance factors of the criteria are however low. The positioning of elements will be solved since special corner elements are used to assure the stability during assembly. Since the corner elements provide the elements stability, the assembly must start from them and the elements position will thus be solved gradually. The loose parts of the connection device are not self guiding. It is estimated that there will occur no mentionable extra assemble time due to lack of self guiding. The positioning of loose parts criteria is therefore not considered as a crucial problem.

The connection device will be further tested with real life models in order to investigate assembly times etc.

Evaluation of easy assembly for floor-to-floor/wall-to-wall connections

The floor-to-floor/ wall-to-wall connection device is also evaluated in the same manner with the help of the *Connection design Method.* The evaluation is performed in order to improve the design with regard to the easy assemble criterion. As discussed earlier a special shear force connection has been developed. The special connection has been developed for situations where the shear forces are extra large; in all other cases the connection, which is described here, is used. The evaluation and the improvements of the special shear force connection are however not described in this case study.

Table 23 Evaluation table concerning easy assembly for floor-to-floor/wall-to-wall connection device.

		**Floor-to-floor/wall-to-wall Connection**	
NUMBER OF CRITERIA USED		15	
MEAN GRADE		1,70	
INDEX		67%	
SUMMARY OF CRITERIA			
Criteria	**Importance**	**Point**	**Grade**
Stability	0	-	-
Positioning of Elements	1	-1	-1
Positioning of Loose Parts	1	-1	-1
Number of Loose Parts	2	-1	-2
Size of Loose Parts	1	3	3
Weight of Loose Parts	1	3	3

Need for Assembly Workers	2	3	6
Safety for Workers	1	1	1
Tools	2	3	6
Accessibility	1	3	3
Fixation Method	2	1	2
Protruding Parts	2	3	6
Multi-Purpose Connections	2	1	2
Fool Proof	1	3	3
Demountability	2	3	6
Tolerance	2	1	2

The positioning of the elements and the positioning of loose parts are scored low in this evaluation. The same reasoning as mentioned for the floor to wall connection device is valid for this connection device as well, i.e. special corner elements are used and the loose parts are not considered to cause extra assembly time. In addition to these criteria the number of loose part criteria is scored low. The importance factor is here a bit higher due to the fact that extra parts to assemble are time consuming. The design is therefore revised before real life testing is initialised.

The *Connection Design Method,* developed by Jürisoo and Staaf (2007), contains a part reduction section (see Figure 33) whose aim is to minimize the parts without loosing functionality. In order to minimize the included parts of the floor-to-floor connection the part reduction test is performed.

MINIMIZE THE NUMBER OF PARTS USING THE FOLLOWING QUESTIONS		
Answer the following questions for each part in the connection. If all questions concerning a part result in negative answers, the studied part could be eliminated or combined with another part.		
Question	**Yes**	**No**
Does the part move relative all other parts?		
Must the part be of another material than other parts?		
Must the part be separated from other parts, or else one or more of the other parts' assembly will be impossible?		

Figure 33 Part reduction formulary from Jürisso and Staaf (2007) Connection Design and Evaluation Method.

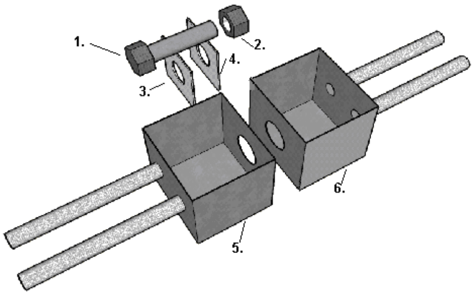


Figure 34 Connection device, floor-to-floor and wall-to-wall.

After the part reduction is performed on the connection device in Figure 34 it is clarified that part 2, 3, 4 and 6 can be eliminated or combined with another part. The solution is that part 3 should be combined with part 1. Part 2, 4 and 6 should be combined to one part. The function of part 2, 4 and 6, when combined, is the same as for the female part of floor-to-wall connection (see Figure 35), i.e. it should resist shear, tension and compression forces. It is therefore possible to optimise the connection by replacing part 2, 4 and 6 with the female part of the floor-to wall connection. The difference is that the load magnitudes are bigger for the floor-to-floor connection. The connection device is therefore checked with the load magnitudes of the floor-to-floor connection. This change does also align with the multi-functionality criterion, since the connection device will be adoptable in all connection situations. The combination of part 1 and 3 can of course also be used in the floor-to-wall connection. The result after the combination of part 1 and 3 and the replacing of part 2, 4 and 6 with the floor-to-wall connection is shown in Figure 35 The result of the part reduction in the floor-to-wall connection is shown in Figure 36.

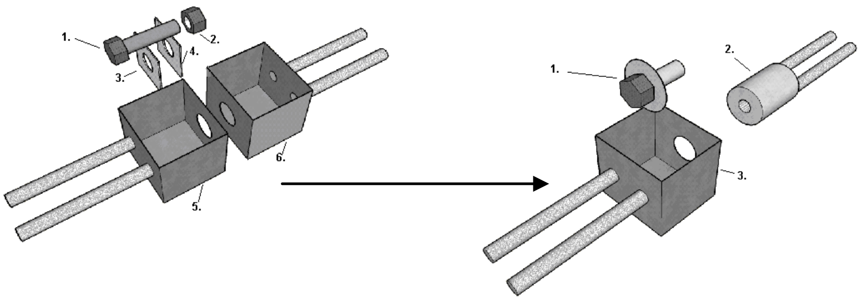


Figure 35 Sketch of floor-to-floor/wall-to-wall connection, before and after part reduction.

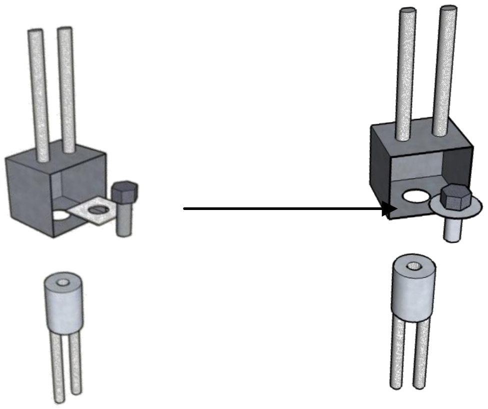


Figure 36 Sketch of floor-to-wall connection, before and after part reduction.

As visualised in Figures 35 and 36 the result of the part reduction is one connection device which is adoptable in all connection situations (except for the case where the shear force is exceptionally large).

Testing

In order to confirm that the connection development has resulted in a connection concept that in reality corresponds with the connection definition, full scale models of the connection devices are manufactured. This is also an acknowledgement of that the connection concept can be manufactured. The connection devices are initially tested without the elements to make sure that the connection design does not have any obvious defects. Finally the connection devices are tested together with the elements in order to see the real function, with regard to assembly time etc.

The tests of the connection concept in this case study correspond to the aim with the design and the concept is therefore delivered to the final design activity.

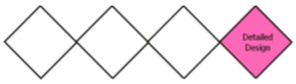
Concluding the activity

In order to conclude this activity the connection development group checks the activity completion table. It shows that all decisions and sub-tasks that concerns activity 3, evaluation and improvements, can be filled with yes. The activity can consequently be concluded.

Table 20 Activity completion table, an activity can be concluded when all sub tasks or decision are made, i.e. when the boxes of interest are ok. The table shows that activity 3 can be concluded (bold).

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and criteria	X	X	Yes
1	The stated activities should be confirmed	X		Yes
1	It should be decided which system concepts that should be investigated	X		Yes
2	Come up with a couple of connection concepts		X	Yes
2	The structural system should be set before the conceptual design can be concluded	X		Yes
2	The connections should fulfil the absolute requirements		X	Yes
2	The connections should fulfil the stressed evaluation criteria to a big extent	X	X	Yes
2	It should be confirmed that the requirement on the system are reasonable	X		Yes
3	Select one concept.		X	**Yes**
3	A real life test should be performed	X	X	**Yes**
4	Optimise the connection and make it ready for manufacturing		X	

Detailed design



The aim with this activity is to give the connection concept its final design and give directives for how the connection concepts should be adopted in project development; when should which connection device be used?

The directives, which are worked out by the connection development group, are implemented in computer programs which should ease the work for the designers while developing a project. The computer programs should on the basis of input, such as house geometry, load magnitudes, geographical position etc. present the number of connection devices and where they should be placed.

Main connection device

The main connection device that is developed can be used as floor-to-floor, wall-to-wall and floor-to-wall connection. The connection device has, after more detailed calculations, got its final design and measurements. The detailed drawing is shown in Figure 37.

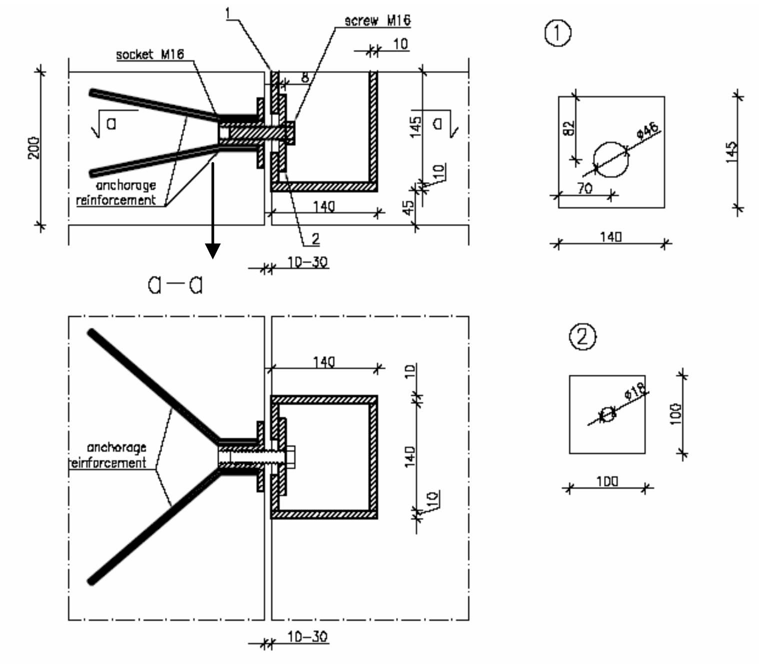


Figure 37 Detailed drawing of the main connection device, Consolis (2007).

Shear force connection device

The shear force connection device is developed in order to resist big shear forces, and should only be used in situations when the shear force is too big for the main connection device. The final design of the shear force connection device is presented as detailed drawings in Figure 38.

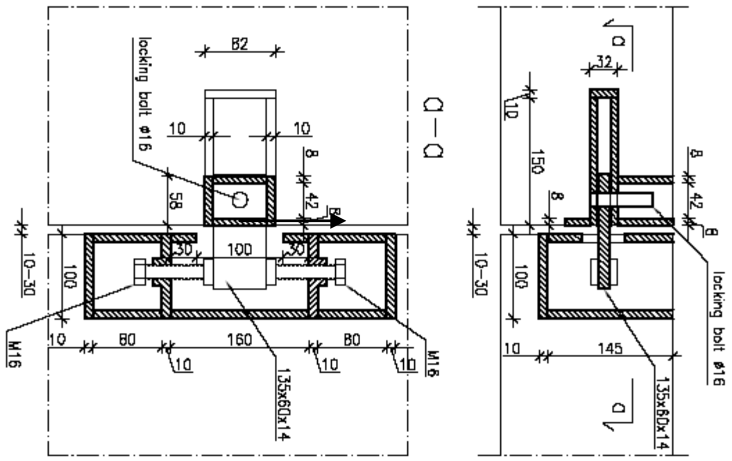


Figure 38 Detailed drawing of the shear force connection device, Consolis (2007).

Concluding the activity

This last activity can be concluded when all decisions and tasks concerning the *detailed design* activity is fulfilled. This is shown in Table 27. This means that the development process can be concluded.

Table 27 Activity completion table, an activity can be concluded when all sub-tasks or decision are made, i.e. when the boxes of interest are ok. The table shows that the activity can be concluded.

Activity	Description	Approved by		Approved
		System	Connection	Yes/No
1	Defining the aim with the connection development, important requirements and conditions	X	X	Yes
1	The stated activities should be confirmed	X		Yes
1	It should be decided which system concepts that should be investigated	X		Yes
2	Come up with a couple of connection concepts		X	Yes
2	The structural system should be set before the conceptual design can be concluded	X		Yes
2	The connections should fulfil the absolute requirements		X	Yes
2	The connections should fulfil the stressed evaluation criteria to a big	X	X	Yes

	extent			
2	It should be confirmed that the requirement on the system are reasonable	X		Yes
3	Select one concept.		X	Yes
3	A real life test should be performed	X	X	Yes
4	Optimise the connection and make it ready for manufacturing		X	**Yes**

Conclusions of the case study

The aim with the case study was to ease the development, and to confirm the content, of the guidelines. It can be concluded that it would not have been possible to develop the guidelines without the case study, since complicated issues that need extra effort has been revealed while simulating the connection development. For example, how the system development and the connection group sets requirement on each other, and in which phase of the activities these requirements need to be communicated. It has also been clarified in which phase which information is needed. For example, before choices of connection concepts (all connections that are needed in a building, in order to transfer the loads to the ground) can be made the structural behaviour of the building must be known.

A disadvantage with the case study is that the system development group's progress has been assumed to be carried out without any iteration. This is unrealistic in a real development progress, since conditions changes and it is impossible to find the right solution from the beginning. This means that in a real connection development process information from the system may become revised and the process will go backwards, which is not described in this case study. The iteration on system level should however stay within the activities, in the same way as in the connection development. The activity completion table should be detailed in such extent that the activity is totally completed when the table is completed. This means that an activity completion table, in a real development process, must be more elaborated. Another difficulty in a real development process, which is impossible to simulate, is misunderstandings. Misunderstandings may aggravate and delay the development process. Further on, simulations of a real life test in the *Evaluation and Improvements* activity are not possible to describe in a detailed and realistic way. The test is therefore only mentioned briefly.

One issue that makes the development process difficult to describe in form of a case study is the fact that oral communication is very hard to simulate. Many decisions and much development work will be performed during meetings, formal or informal, in a real development process. It is also easier to explain requirements and evaluation criteria if some one does not understand. It should be emphasised that all decisions and all progress should be documented in a formal way even in a real development process.

Conclusions and Discussion of the method

As discussed above, the purpose of this section is to facilitate the adoption of industrial thinking in the development processes in the building industry. The aim is to create a method for the development of connections for industrial building systems. The method developed consists of clearly predefined activities with articulated breakpoints. A breakpoints means that all involved actors decides whether the process should proceed or not. A check should be made, which should give answers to the following questions: are all sub-aims fulfilled and is the main aim of the development process achievable? To a high degree, the new knowledge in this work consist of that the intuitive and creative activities are explicitly defined.

The approach, which includes predefined activities, will encourage planning of the development process and the development group will get clearly stated sub-aims. Planning of the process will help the developers to prioritise between different assignments and it is easier to focus on the right thing at right time. This means that the total resources are used effectively, which complies with the industrial thought. The method includes continuously reporting. One of the reasons for this is that a development group should do a follow-up after a completed project. This follow-up will support future development projects, which can be more efficient and resources could be even more effectively used.

The developed method contains predefined activities: *Definition, Conceptual design, Evaluation and improvements* and finally *Detailed design*. In the first activity are stated a *definition* of the development process and a definition of the important requirements and criteria on the connections. *Conceptual design* is the most time-consuming activity and when the most of the development work is performed. This activity results in a hand full of connection concepts. *Evaluation and improvements* aims to choose one of these. This activity should also result in improvements of the concepts. In the *detailed design* activity the connections should be prepared for manufacturing and be ready to be adapted in the projects.

Deciding to close a process can be more difficult than starting one. Therefore, in this method each activity is iterative but the whole development process is not. Between the activities there are articulated breakpoints. This means that when an activity has started it is not possible to go back to the previous one; the choice to initiate an activity is irreversible. In a breakpoint the developers should make sure that the quality of the developed product is as expected. The breakpoints do also function as a moment of afterthought; can the developed product gain profits or should the development project be stopped? The progress of the development process should be slow and the breakpoints allow evaluation of the accomplished work. Without breakpoints it is easy to go on with a process that was doomed from the beginning.

It has not been investigated how a real development group would have experienced a development process that is not iterative. Today developers are used to be able to go backwards in the process and recall decisions and redesign solutions. This is one of the reasons for the inefficiency of the construction industry. To change the way of thinking may be hard and time-consuming. Before developers get used to a slow progress that does not allow iterations the development process may lead to failed solutions. This means that gradual transition to non-iterative processes is needed.

This report suggests that this way of dividing the development process in activities should be standardised. It must not specifically be the four activities that are presented in this section, since every new project has different conditions and aim. This project addresses connection development but the method's procedure can easily be adapted to development of other components in other parts of the construction industry. In that case, the requirements and evaluation criteria will of course be different. In addition, the idea of dividing the development process into activities may be implemented into other areas within building industry, for example development of a building system or a building project. Indeed, the idea for the connection development method origins from a method for architectural design. In the latter case, the suggested activities in this report cannot be directly implemented, since other demands are set on the development process, such as investigations of customers' needs.

The method also includes non-static documents that should be updated as the development process proceeds. A thought from the beginning of the Master's project was to standardise for example requirement on connections, a part request form. The work has shown that it is hard, or even impossible, to predefine requirements that are valid for all connection types and situations. In addition, it may not even be desired due to the fact that it may lead to misaimed requirements and that important requirements are left out. It is therefore better to complete requirement and evaluation criteria documents as the process proceeds and new information is known. This also makes the developers more alert and they must think about consequences of set requirements and criteria and how things are related to each other. This Master's project suggests that the use of non-static document in development processes should be standardised. The document set-up should then be optimised for each new development process.

For further studies it is recommended by the authors that the method for connection development should be the foundation for a similar method for the development process of a building system. The connection development process treats several parts of the system development, since connections are a central part of the prefabrication industry, and to a large extent the developed method for connection development should be able to be used. The real development process of connections can be properly described only when it is a part of the system development process. It is suggested that the method should then be tested in a real development process. The method could then be evaluated and improved.

Identification of Design Methods and Guidelines

IN the context of the structured development method given above, below is suggested a method for design and evaluation of structural connections in building structures which make elements easier to assemble. The method is a so-called Design For Assembly method, which are rgualr features in the manufacturing industries. In this specific chapter design methods are identified and summarized. All methods treated concern the assembly because this is a potential cost saver in building industry. However, the first section handles general information of design methods.

Design Methods

As introduced in Chapter 1, there exist several different design methods in the manufacturing industry. The design methods can be developed for Quality, Reliability, Manufacture, or Assembly etc. A good design is preferred to be performed by a designer in cooperation with a manufacturer. Products designed this way are generally well suited to ease manufacturing and the products will still fulfil the original requirements. The opposite is when the design team performs the design without any influence from any manufacturer, which can lead to a product that is difficult to produce. This is, according to Boothroyd *et al.* (2002), figurative called over-the-wall design as the designer only hands over the blueprint with no further communication. Fore the same reason, assembly workers must be included in the design process.

Generally, the information presented in the methods gives some form of guidelines of how to think in different situations, but also suggestions on the design processes. However, general information valid for all these methods will first be presented. The studied design methods can be of different kind; Guidelines, Qualitative methods and Quantitative methods. The studied methods include at least one of these.

Guidelines: Only design principles and guidelines are not fully sufficient when different designs should be compared or when a design should be refined. Guidelines, without ranking, cannot evaluate a design since they are just a set of rules, according to Boothroyd *et al.* (2002). However, guidelines are important as a base for a design method were they provide the designer with background information.

Qualitative methods: With a qualitative evaluation method, it is possible to rate different designs and compare them to each other. These methods compare different designs relatively to each other without measurable values.

Quantitative methods: If the time or cost saving for a redesign is desired, it is necessary to use a quantitative method. To calculate the time saving or the cost saving for a redesign, a database containing the time and cost for a certain operation is needed. This can also be called a knowledge-based approach.

Knowledge from the Precast Concrete Industry

In the precast concrete industry, elements and element connections have been developed during many years. Therefore it is important to consider this knowledge when development of a design method for connections in industrial constructions is carried out. In this section the most relevant guidelines will be presented, but it starts describing possible ways to connect precast concrete elements.

Connection Types

Today precast concrete elements are usually connected by bolts, grouting on site, reinforcement embedded in epoxy or by welding. Details that are connected by screws are often preferred prior to welded and grouted connections because they are faster and cleaner. Using screws and bolts is simple and safe, but on the other hand it demands more narrow tolerances. Reinforcement bars or screws can be fastened to elements in different ways; cast into an element, grouted into a drilled hole or glued to the elements. Grouting on site does not require small tolerances and the connections get strong. The quality is however weather depending, and it is not very time efficient. Gluing is not only dependent on weather, but the quality also depends on cleaning and drying. Welded connections are often easy to fit and adjust, but there can be a lack of quality level depending on the workmanship. Furthermore, welding is an unsafe fixation method with regard to i.e. worker safety, material damage and risk for fire. An example of assembly with prefabricated beams is shown in Figure 39. A threaded rod, which is normally cast into the support or fastened using a threaded insertion, is inserted through a hole in the beam. Often the threaded rod is fastened by nuts on the top of the beam and then grouted. If the hole is grouted the connection will be more ductile than without grouting. (Betongvaruindustrin, 2005)

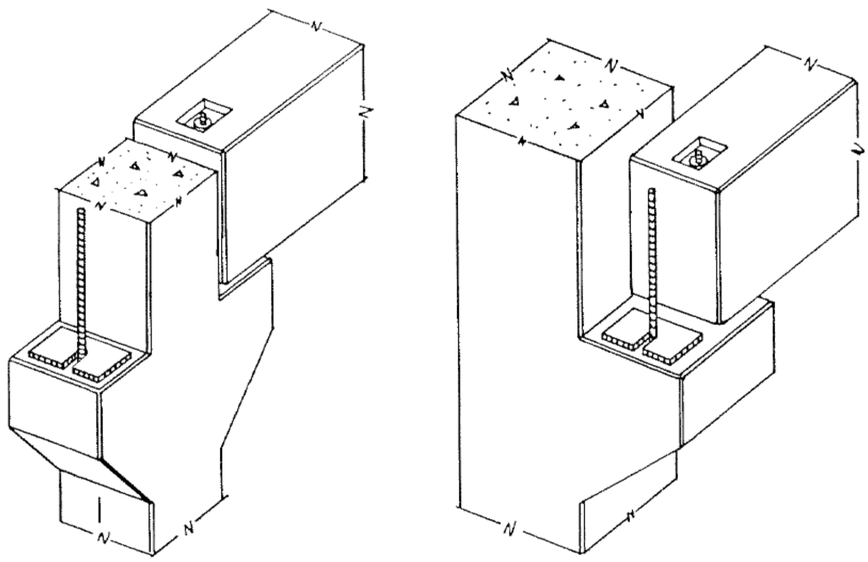


Figure 39 Examples of beams connected to columns, from Betongindustriens Landsforening (1996).

Guidelines for Precast Concrete

There are some guidelines regarding the erection of prefabricated concrete elements, according to *fib* (2007). These are shortly described below:

Accessible connections: Use connection types that are possible to access both during erection and afterwards.

Handling damage: Avoid parts that are fragile when handled. Parts that project from an element are in a vulnerable position. There is also a possibility to damage other elements with these parts.

Hook-up time: The time used for crane operation should be held to a minimum as it is expensive. Each element should be lifted into position and be put down so it is stable before it can be unhooked.

Load cases: There might be varying loads during the erection. All possible load cases have to be considered.

Plan the assembly: Make sure that all movements necessary for erection are possible to perform.

Reinforcement positions: All parts projected from an element should be designed so that they do not collide during erection.

Stability of the elements: Temporary supports should be prepared before the element is lifted into place.

Stability of the structure: The structure must be stable during the erection to avoid collapse.

Standardisation: Standardised connections should be used for similar situations as the need for skilled workers and the chance for errors decreases.

Also the size of the components should be standardised to minimise the number of different parts.

Weather resistance: Avoid materials that are sensitive to varying weather, such as grout, epoxies and on-site cast concrete.

Design for Manufacture and Assembly ®

Boothroyd-Dewhurst Inc. has developed a design method called Design for Manufacture and Assembly (DFMA). It is a combination of DFM and DFA where DFM is aimed to ease the manufacturing process of the parts that will form a product and DFA is, as indicated above, a method to ease the assembly process. This could be achieved by reducing the number of parts needed for an assembly and the product should be as easy as possible to assemble with few possibilities for misassemble. This method is mainly developed for manufacturing and assembly of small products.

This section starts with a short description of the DFMA method and is followed by describing guidelines that are the base for the DFMA method, defining criteria for part reduction and assembly efficiency. Furthermore, time penalties for the evaluation method are described for several situations. In the end, some assembly methods are described. Unless otherwise is stated, the information in this section comes from Boothroyd *et al.* (2002).

Design Procedure

When designing according to DFMA the first part is DFA, which is important even if the assembly cost is low. This is because the DFA method, for example, reduces the number of parts which leads to a reduced manufacturing cost. A design for assembly also results in improved reliability and fewer defect parts. In Figure 40 the design procedure according to the DFMA method is presented. When the first DFA analysis is completed it might be necessary to carry out a DFM evaluation to make sure that the manufacturing process is not complicated by the changes due to assembly.

The method starts by minimising the number of parts in order to get an easier assembly. Thereafter the assembly time is calculated due to handling and insertion of parts. This is done using handling codes and insertion codes each giving time penalties which will be summed up to a total assembly time.

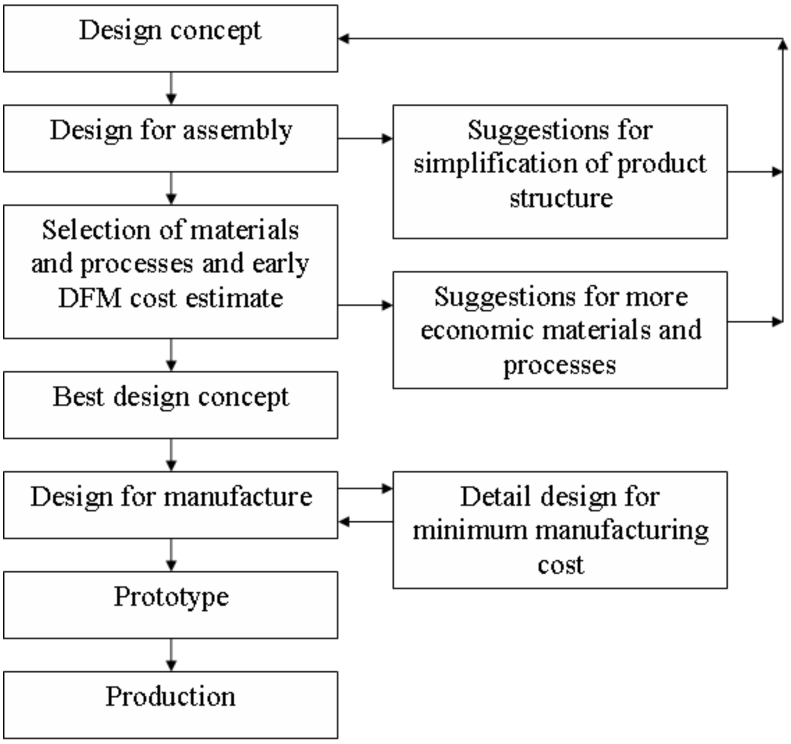


Figure 40 DFMA design procedure according to Boothroyd et al. (2002)

Assembly Guidelines

This section is divided into general guidelines, guidelines regarding handling and guidelines regarding insertion and fastening.

General Design Guidelines

Avoid over-constrained design: Use kinematic design principles to avoid an over-constrained design. Kinematics describes motions of bodies. Here, the interest is to fix parts without too many fixation points. This means that it can be possible to simplify the fixation of a part. A connection consisting of, for instance, three screws might be possible to simplify to just use one screw and one support. In this way, fewer screws or fasteners might be sufficient to keep the part stable and still transfer design actions.

Avoid restricted access: Make sure that there is enough space left for assembly operations. Place fasteners where they can be easily reached by the assembly worker.

Minimise the number of parts: The assembly cost is mainly influenced by the number of parts and their ease of handling, insertion and fastening. The number of parts in an assembly should always be kept to a minimum.

Use one material: If a stronger material is needed in some regions of a part, try to use the same stronger material in both regions even if it is more expensive. The savings in assembly will probably be greater than the cost for the more expensive material.

Guidelines Regarding Handling

Jamming and tangling: Prevent parts from jamming and tangling when stored and handled. If the parts tend to jam or tangle a lot of time might be needed to loosen the parts which also may require both hands of the assembly worker. Small changes in design may be sufficient to avoid jamming and tangling.

Others – small, sharp, slippery etc.: Avoid parts that stick together, fall apart or are slippery. Also avoid having too large or too small parts and parts that are fragile or sharp. All these properties can decrease the efficiency of assembly.

Standardise components: Avoid having one part for the right side and another part for the left side; try to use standardised parts within the assembly. A reduced number of different parts decrease the possibilities for misassemble and the cost for specific parts.

Symmetry: Parts are preferred to be as symmetrical as possible; they should preferably have end-to-end symmetry and rotational symmetry. Time can be saved if a part can be assembled in many orientations as the need for rotation and location is reduced. If a part needs to be asymmetrical for any reason, it can be slightly asymmetrical or pronounced asymmetrical. For manual assembly the parts should be made clearly asymmetrical. On the other hand, for robotic assembly it depends on if a visual system is available. With a visual system, a robot uses cameras to locate parts and to manoeuvre. A visual system might be expensive, but if it exists it can be sufficient to have just slightly asymmetrically parts. If there is no visual system, the asymmetry must, in some cases, be even more pronounced than for manual assembly. Boothroyd *et al.* (2002) states that a pronounced asymmetry is needed for robotic assembly due to the cost for a visual system, while Causey (1999) claims that only a small asymmetry is sufficient for robotic assembly.

Guidelines Regarding Insertion and Fastening

Assemble from above: The best way to assemble is, in general, around an axis from above, as the parts will stay due to gravity. If fastened from below it might be necessary to hold the part until fastened or inserted.

Avoid repositioning: Avoid turning over the incomplete assembly during the assembly.

Locate before release: Parts should be located before they are released. If a part must be released before it is located, there is a risk that the part will not be located correctly, e.g. when dropped in a hole.

Resistance to insertion: Provide generous tolerances for insertion in order to avoid friction and jamming during insertion. The mating parts should preferable be guided to the right location.

Secure parts: Loose parts should be secured as soon as possible after being located, otherwise time will be needed to hold down the parts in position. Self-locating parts are preferred.

Use simple fasteners: For manual assembly snap fits fasteners are preferred. Snap fits are the cheapest fasteners followed by plastic bending, riveting, and finally screw fasteners.

Criteria for Part Reduction and Assembly Efficiency

The DFA method starts reducing the number of parts, in order to ease the assembly, by answering the following questions:

- Does the part move relative all other parts?
- Must the part be of another material than other parts?
- Must the part be separated from the other parts, or else one or more of the other parts' assembly will be impossible?

A part that gives negative answers to all of these questions is superfluous. If the answer is positive to one or more of the criteria, the part considered is a critical part. The sum of all critical parts is called the theoretical minimum number of parts, n_{min}.

To be able to improve a specific assembly, it is important to know its assembly efficiency. The assembly efficiency, E_a, can be calculated by multiplying the theoretical minimum number of parts, n_{min}, to the basic assembly time for one part, t_{ba}, and then divide the sum by the estimated total assembly time, t_{ea}, see Equation 1. The basic assembly time is defined to be three seconds if there are no problems concerning handling, fastening or insertion, which is further discussed later.

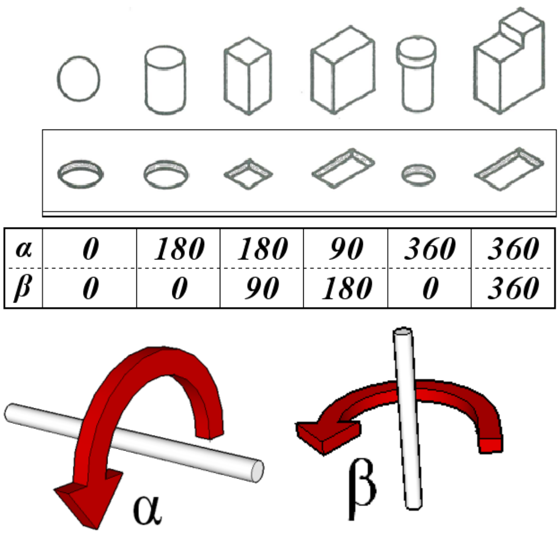
$$E_a = \frac{n_{\min} \cdot t_{ba}}{t_{ea}} \qquad (1)$$

Assembly Evaluation

When an assembly process is to be classified, or when different designs are to be compared, it is necessary to consider several actions. First it is necessary to collect the parts to the place for assembly, so that all parts are within reach for the assembly worker. Sometimes several parts can be brought to the assembly station at the same time which leads to time savings. Then the parts have to be moved to their location in the assembly. This operation includes grasping of the parts and the actual movement of the parts. Further on, it might be needed to rotate the parts before they are in their right position. When inserting parts, there can be problems with e.g. jamming or friction which has to be considered. Next step is to fasten the parts. This operation demands various amount of assembly time depending on the kind of fastener and if the parts have to be held in position before fastening. If an assembly has to be turned over in order to perform the assembly work, extra time is needed. All operations described above demand some assembly time which has to be estimated. The time needed can be estimated by an analysis of the parts' properties, which is described below for some different properties. The times discussed are considered as penalty times given for different types of assembly problems. It might be possible to orientate a part while it is moved. Thus it might not always be correct to add the time penalties of different causes. Such a time penalty would be overestimated.

Symmetry Effects

The symmetry of a part can be defined with two angles; α and β. α-symmetry is the rotation angle that the part needs to be rotated around an axis perpendicular to the axis of insertion and β-symmetry is the rotation angle the part needs to be rotated around the axis of insertion, see Figure 41. Boothroyd *et al.* describe a total angle of symmetry which is the sum of α and β. The advantage of this approach is that only one single parameter is needed in order to get the time needed for rotation.



α	*0*	*180*	*180*	*90*	*360*	*360*
β	*0*	*0*	*90*	*180*	*0*	*360*

Figure 41 α and β symmetry, adopted from Boothroyd et al. (2002).

Size and Weight Effects

Handling time is influenced by the parts geometry. The thickness is defined as the maximum height of the thinnest direction from a flat surface. For cylinders (with diameter < length) the thickness is defined as the radius. A handling time penalty of up to 1.2 seconds will be the result of a thickness under 2 mm. Further on, the length is defined as the largest non-diagonal dimension of the part considered. A length less than 20 mm will result in a handling time penalty. These time penalties are due to the difficulty to grasp small parts. Parts that are so small that they need to be handled by tweezers should be avoided. The handling time penalty also applies for heavy parts which are calculated assuming manual assembly using one hand.

Additionally Effects

Both weight and size may cause the need for a two hand grip. Two hands might also be needed if the part is flexible, if the part needs to be handled carefully or if holding features are missing. Also tangling or nestling usually demands both hands.

Effects due to Chamfer Design

Chamfers are used to ease the insertion of a peg into a hole or the placement of a part with a hole onto a peg. There are formulas for calculation of the insertion time of a certain chamfer design. With chamfers both on the peg and the hole the insertion time will be approximately half the time as the insertion time would be without chamfers. It is more effective to have a chamfer on the peg than on the hole, and curved chamfers are more effective than conical but they are on the other side also more expensive.

Effects of Access, Vision and Special Fasteners

Time penalties up to seven seconds are given for screws assembled with restricted vision and clearance. Also the design of screws is considered. There is a time difference for screws fastened by hand or with help of a power-tool. The time penalties are derived from experiments. The penalty due to restricted access is up to one second while combined restrictions of access and vision result in a penalty of up to three seconds.

Effects of Holding Down

There is a basic time when inserting a peg through a hole in at least two materials that are prealigned and self locating. In addition to the basic time a time penalty is added if the materials need to be held down or to be aligned. The penalty time will vary depending on if the parts need to be held down and if they are easy to align or not. The time penalties vary significantly.

Application of the Methodology

Each assembly is given a handling code, consisting of two digits, which describes the difficulty of handling the part to be assembled. These handling codes can be seen in Table 28. The first digit concerns the symmetry (α and β) while the second takes into account the handling difficulties and thickness. An estimated average handling time, based on experiments, is given on the basis of the handling code; thus a time data base is needed. Times for insertion and fastening are calculated by formulas for different types of operations depending on for instance chamfer design and clearance. These formulas are not considered further in this project. Times for acquisition, i.e.

times needed to collect material and equipment, also have to taken into account.

A total assembly time, t_{ta}, can be calculated from the average times, see Equation 2. Here the acquisition time, t_{acq}, is added to the number of parts, n, times the sum of the handling time, t_h, and the insertion time, t_i.

$$t_{ta} = t_{acq} + n \cdot (t_h + t_i) \qquad (2)$$

The average times discussed previously can be changed a lot for different types of assemblies. For example, the time to manually fasten a screw is 8.2 seconds on average but if the screw is auto fed the fastening time can be reduced to 2 seconds. For a large assembly a screw can require even longer time to be fastened.

The possibility to eliminate parts can be evaluated using the three conditions discussed earlier in Section 0. Further on, the DFA index can be calculated and the cost can be estimated by adding the total part cost to the cost of the assembly workers per hour times the total assembly time. A table of possible eliminations or design changes can be created. The table can also show the time saving of each design change.

Table 28 Examples of handling codes according to Boothroyd et al. (2002).

Handling codes, shown in the grey fields, depend on symmetry and size		No handling difficulties			Part nests or tangles		
		Thickness > 2mm		< 2mm	Thickness > 2mm		< 2mm
		Size > 15mm	6mm > Size > 15mm	Size < 6mm	Size > 15mm	6mm > Size > 15mm	Size < 6mm
		0	1	2	3	4	5
α+β < 360	0	1.13	1.43	1.69	1.84	2.17	2.45
360 < α+β < 540	1	1.5	1.8	2.06	2.25	2.57	3.0
540 < α+β < 720	2	1.8	2.1	2.36	2.57	2.9	3.18
α+β = 720	3	1.95	2.25	2.51	2.73	3.06	3.34

Manual Assembly Methods

The times needed for part acquisition presented in the DFMA method are for small parts and when all parts are within an arm length from the assembly worker. No major body motions are assumed to be required. If the parts are further away from the worker or heavy or large, other time figures are needed. There are different kinds of assemblies, namely Bench assembly, Multistation assembly and Modular assembly centre, which can handle part sizes up to about 85 centimetres. Custom assembly layout and Flexible assembly layout suit parts that are larger. All these assembly methods concern assembly on a special assembly place, which is not always possible. For instance when installing an elevator, the assembly has to be performed on site. This will result in an increased handling time when tools, material and parts need to be transported. The time for acquisition differs depending on the location of the parts, the distance from a part to its assembly, the part weight and if one or several parts are collected on the same time. Boothroyd *et al.* have divided parts into three weight categories starting with normal parts able to be handled by one person. If the part is heavier, two persons are needed for the handling, and for even heavier parts lifting equipment is needed.

Design for Manufacture

When a DFA analysis is completed a DFM analysis follows. For the manufacture of a specific part many combinations of processes and materials can be chosen. For instance, one material can be sand cast while another material can be processed by injection moulding. The processes and materials available can be more or less easy, or even impossible, to combine. Membership functions can be used to see if a chosen combination is possible. A membership function gives a value between zero and one where zero means impossible to manufacture and one means easy to manufacture. The values are depending on the material, size, shape etc. There are some computer programs that guide the designer through the choices of manufacturing. Programs can be built up using conditions as; if condition A and B are fulfilled than action C will be initiated. Also the strength and modulus of elasticity of the available materials have to be considered. Further on, it is important to get a cost estimation of the manufacture. An estimated cost can be calculated with computer programs. The cost depends on shape, material, processes and quantity.

Design for Assembly According to Bralla

There is a design-for-manufacture handbook written by Bralla (1999) which also handles design for assembly (DFA). Bralla's method consists of guidelines that are similar to the guidelines in the DFMA method developed by Boothroyd *et al.*, described in the previous section. The method starts with minimising the number of parts, also inspired by Boothroyd *et al.*, and continues with simplifications of the remaining parts using guidelines. Most of the guidelines are the same as in the DFMA method but some are different or more detailed, these are described below:

Add parts: In some cases, an improvement can be achieved by adding an extra part as this might allow more liberal tolerances. It is though important to avoid adding too many parts to a design.

Design over-sized holes: When inserting, for example, a peg into a hole, it is beneficial if the hole is of over-size. This is for the same reason as the previous point, self-guiding, but also due to the risk of jamming.

Gather all electronics: Try to locate all electronic components in the same place of a product. In this way no extra wires are needed between different components. With all components in the same location the rest of the part might be easier to design.

Minimise the amount of fasteners: It is better to have few large fasteners than many small. In this way the time for assembly will be decreased, but also the time spent on handling loose parts.

Use integrated hinges: For some materials, especially plastics, hinges can be made within a part. Integral hinges can be achieved if a thinner section is formed at the location for the hinge. In this way, material can be saved.

Use integrated springs: In many cases, springs can be difficult to mount. Therefore, when it is possible, parts should be designed to act in a flexible way to avoid the need for extra springs.

Use self-aligning parts: In order to minimise the assembly time, self-aligning parts should be used. With self-guiding parts, the assembly position do not need to be exact in order to mount the part.

Lucas Design for Assembly Evaluation Method

This knowledge-based method, called the Lucas DFA evaluation method, is built up around an assembly sequence flowchart and it has grades derived from studies. The method is best suited for production of small products. This section is based upon a study on the DFA evaluation method, made by Redford and Chal (1994). The method is systematic; important aspects of assemblability and component manufacture are considered and rated. The design evaluation follows the procedures shown in Figure 42, here including design for manufacture. The evaluation starts with a product analysis where it is important to decide if the design is unique. If a similar design exists, there might be an opportunity for standardisation. Usually, other DFA systems only consider the current assembly and do not use the knowledge from previous designs.

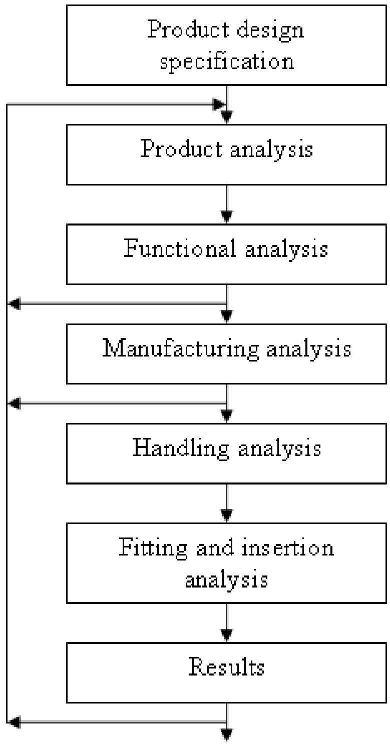


Figure 42 The Lucas DFA procedure, according to Redford and Chal (1994).

The next step in the procedure is a functional analysis of the assembly. Different activities are categorized by their functionality. Each part in the assembly is analyzed and assigned to be either essential (Category A) or non-essential (Category B). The design efficiency, E_d, is then defined as the ratio; number of essential parts, n_A, divided by the total number of parts, n, see Equation 3. Assembly cost can then be reduced by eliminating or combining parts that are non-essential.

$$E_d = \frac{n_A}{n} \qquad (3)$$

To eliminate complex designs containing few complex parts an additional design for manufacture (DFM) analysis is carried out as the next step in the procedure. This is necessary as few complex parts might result in a greater cost for manufacture than the gain in easier assembly.

The DFM analysis is followed by an analysis of the handling (or feeding). The analysis includes questions about for example tangling, nesting, fragility, etc. resulting in a handling index, I_h, for each part. In Table 29 the index is presented depending on each of the following subjects; the parts’ size, weight, orientation, handling difficulties and rotational orientation. If the index is under 1.5 the part is satisfying else improvement suggestions are given. A total handling ratio, R_h, for the whole assembly is determined as the sum of all handling indexes divided by the total number of essential parts, n_A, as shown below in Equation 4.

Table 29 Handling index for the Lucas DFA method, adopted from Chan and Salustri (2005).

Handling Index: $I_h = A + B + C + D$

A	**Size and weight of parts** (One of the following)	Very small – requires tools	1.5
		Convenient – hands only	1.0
		Large and/or heavy – requires more than one hand	1.5
		Large and/or heavy – require hoist or two people	3.0
B	**Handling difficulties** (All that apply)	Delicate	0.4
		Flexible	0.6
		Sticky	0.5
		Tanglible	0.8
		Severely nest	0.7
		Sharp/Abrasive	0.3
		Untouchable	0.5
		Gripping problem / slippery	0.2
		No handling difficulties	0.0
C	**Orientation of part** (One of the following)	Symmetrical – no orientation required	0.0
		End to end – easy to see	0.1
		End to end – not visible	0.5
D	**Rotational orientation of part** (One of the following)	Rotational symmetry	0.0
		Rotational orientation – easy to see	0.2
		Rotational orientation – hard to see	0.4

$$R_h = \frac{\sum I_h}{n_A} \qquad (4)$$

The method continues with a fitting and insertion analysis using sequence flow-charts. To be able to identify processes that are expensive, each individual process is assigned a fitting index, I_f. The part fitting index, which is presented in Table 30, has a maximum recommended value of 2.5 and gives an indication of how these processes might be changed. The insertion analysis includes holding, gripping, insertion and other actions e.g. movements and transports. Finally a fitting ratio, R_f, is calculated, see Equation 5, as the sum of all fitting indexes divided by the total number of essential parts.

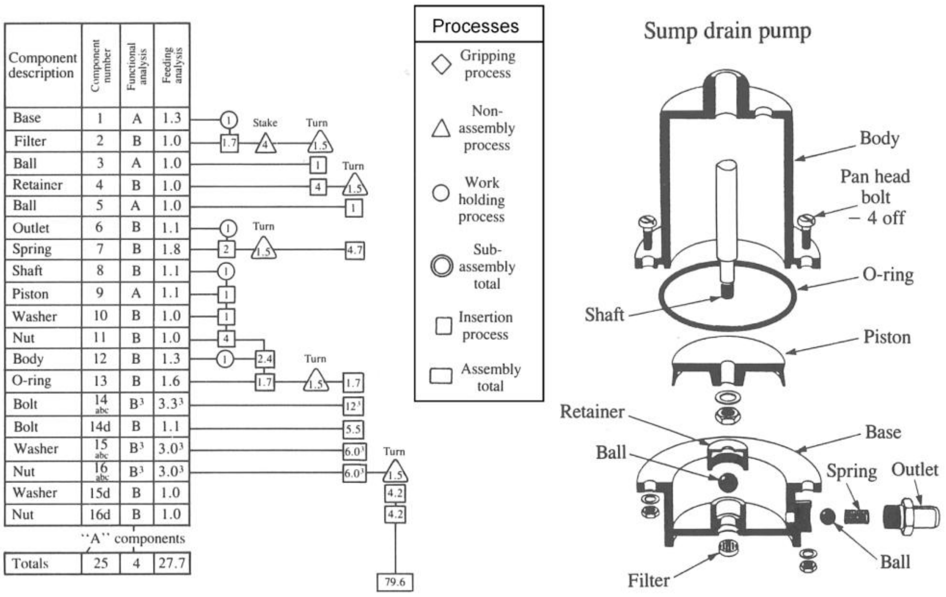
Table 30 Fitting index for the Lucas DFA method, adopted from Chan and Salustri (2005).

Fitting Index: $I_f = A + B + C + D + E + F$

A	**Part placing and fastening**	Self-holding orientation	1.0
	(One of the following)	Requires holding	2.0
		Plus one of the following	
		Self-securing (i.e. naps)	1.3
		Screwing	4.0
		Riveting	4.0
		Bending	4.0
B	**Process direction**	Straight line from above	0.0
	(One of the following)	Straight line not from above	0.1
		Not a straight line	1.6
C	**Insertion**	Single	0.0
	(One of the following)	Multiple insertions	0.7
		Simultaneous multiple insertions	1.2
D	**Access and/or vision**	Direct	0.0
	(One of the following)	Restricted	1.5
E	**Alignment**	Easy to align	0.0
	(One of the following)	Difficult to align	0.7
F	**Insertion force**	No resistance to insertion	0.0
	(One of the following)	Resistance to insertion	0.6

$$R_f = \frac{\sum I_f}{n_A} \quad (5)$$

In order to get more understanding an example of a drain pump, according to Redford and Chal (1994), is shown in Figures 43 and 44 below. In the example, an original design is compared to an improved design.



Design Efficiency:

$$E_d = \frac{n_A}{n} = \frac{4}{25} = 16\%$$

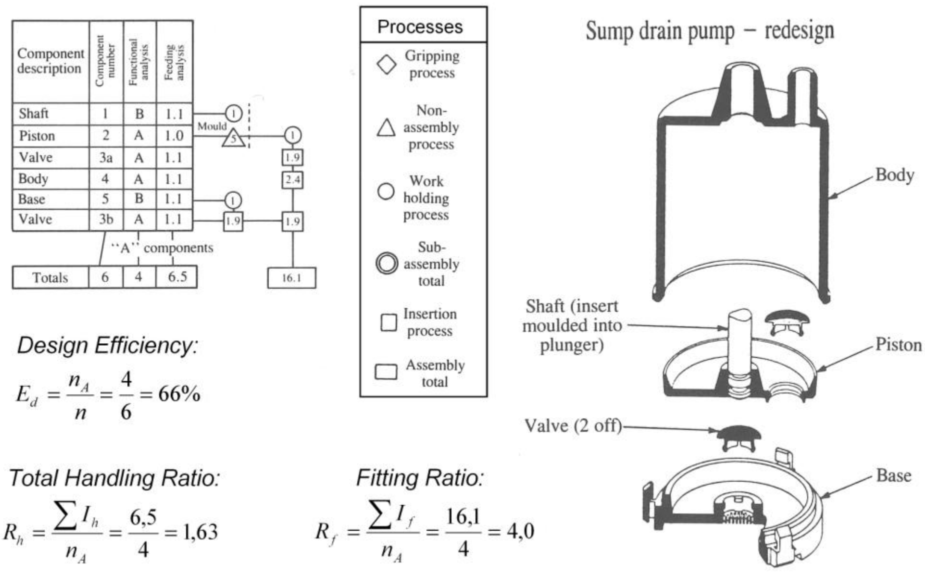
Total Handling Ratio:

$$R_h = \frac{\sum I_h}{n_A} = \frac{27{,}7}{4} = 6{,}9$$

Fitting Ratio:

$$R_f = \frac{\sum I_f}{n_A} = \frac{79{,}6}{4} = 19{,}9$$

Figure 43 Sequence assembly flow-chart for a drain pump, original design, adopted from Redford and Chal (1994)



Design Efficiency:

$$E_d = \frac{n_A}{n} = \frac{4}{6} = 66\%$$

Total Handling Ratio:

$$R_h = \frac{\sum I_h}{n_A} = \frac{6{,}5}{4} = 1{,}63$$

Fitting Ratio:

$$R_f = \frac{\sum I_f}{n_A} = \frac{16{,}1}{4} = 4{,}0$$

Figure 44 Sequence assembly flow-chart for the drain pump after improved design, adopted from Redford and Chal (1994).

The Hitachi Assemblability Evaluation Method

In the late 70-ties, the Hitachi Assemblability Evaluation Method (AEM) was developed by *Hitachi Ltd* and it is described by Redford and Chal (1994). The main objective of the method is to improve design quality by identifying weaknesses in the design at an early stage of the design process. According to the Hitachi method it is important to consider both the cost and the quality of an assembly due to the fact that simple and cheap parts do not always give the least expensive design. Therefore the method measures both the cost and quality by two ratios:

1. An assemblability evaluation score ratio, E, used to estimate the design quality by determining the difficulty of operations
2. An assembly cost ratio, K, used to estimate assembly costs

The Hitachi AEM is based on a procedure starting with categorizing possible assembly operations into approximate 20 elemental assembly tasks. Each task is given a symbol clearly indicating the content of the task. These tasks relate to insertion and fastening but not to part handling. Each elemental task is then given a penalty score, P_s, which reflects the degree of difficulty of the task. Different factors that might influence the elemental tasks are treated as coefficients modifying the penalty score. The definition of the assemblability evaluation score, E_{part}, of the task is the sum of all penalty scores subtracted from the highest possible score, 100 points, see Equation 6. Finally the total assemblability evaluation score for the product, E_{tot}, is defined as the sum of all assemblability scores of the individual tasks, divided by the number of parts, n, see Equation 7. If the value is under 80, improvements should be made. The total score does not provide all the information concerning reduction of the number of parts; it is still possible to improve the score by increasing the number of parts with higher-than-average assemblability evaluation score. To avoid this, a cost ratio, K, is used, see Equation 8. The ratio is defined as the assembly cost of the redesigned product, C_{re}, divided by the assembly cost of the original product, C_{orig}. If the ratio is higher then 0.7 improvements are made. The results of the method are confirmed by continuously comparing estimated assembly cost ratio with the actual ratio. If the difference is small it is acceptable otherwise an examination is carried out to determine possible errors. An evaluation example of a connection is shown in Figure 45.

$$E_{part} = 100 - \sum P_s \qquad (6)$$

$$E_{tot} = \frac{\sum E_{part}}{n} \qquad (7)$$

$$K = \frac{C_{re}}{C_{orig}} \qquad (8)$$

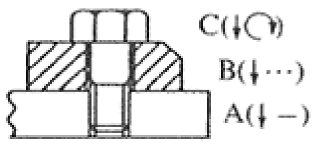
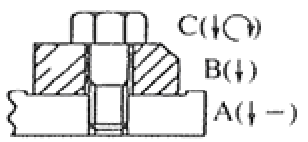
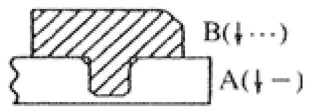
	Product structure and assembly operations		E_{part}: Part assemblability evaluation score	E: Assemblability evaluation score	K: Assembly cost ratio	Part to be improved
First design		Set chassis A	100	73	1	B
		Bring down block B and hold it to maintain its orientation	50			
		Fasten screw C	65			
1:st redesign		Set chassis A	100	88	app. 0.8	C
		Bring down block B (orientation is maintained by spot-facing)	100			
		Fasten screw C	65			
2:nd redesign		Set chassis A	100	89	app. 0.5	B
		Bring down and pressfit block B	80			

Figure 45 Example of evaluation according to the Hitachi assemblability evaluation method, adopted from Redford and Chal (1994).

Design for Assembly On-Site

Lassl and Löfgren (2006) have developed the method design for assembly on-site, DFA(OS), which consists of guidelines concerning assembly at construction sites. Some of the conclusions will be presented in this section.

As discussed in the previous chapters the assembly should be quick, easy and clean. It is also important that the elements are assembled in their final position from the start, with small help from large tools and robotics. Further on, Lassl and Löfgren discusses that connections should be made in such way that they only need to be locked from the inside of the building, which eliminates the need to work on the outside on the façade, which could be difficult. Further discussed are the needs for movement of special tools during construction. It is the opposite of the manufacturing industry where special tools can be fixed at one location. The method includes guidelines presented below.

Assembly order and stability: Elements are preferred to be assembled from the top down. If an element should be possible to disassemble in the future without demounting the whole building, it should be mounted from the side. This is due to the fact that it is impossible to lift an element with another one on top of it. To avoid temporary supports an element can be designed with moment resisting connections which makes it stable without further support.

Flexibility: It is important that the connection is flexible and able to use in different ways. It should be possible to mount and lock the connection from different directions. It is still essential that the connection does not get too complicated.

Handling and ergonomics: Elements are often moved by cranes, which have limited precision. Therefore self-location elements are preferred. Connection details can also be used as lifting points for the elements with the demand that the elements are able to hang straight. The assembly workers' ergonomics is another important aspect, over-head work and use of ladders should be avoided.

Design for Assembly 2

IVF, the Swedish engineering industry's research institute, has developed an assembly method called Design for assembly 2, DFA2, and it is presented by Rapp and von Axelson (2003). The evaluation method gives both a qualitative and a quantitative judgment of industrial assembly processes. The qualitative judgment is based on assemblability and gives a grade, while the quantitative judgment is based on the time needed for assembly operations given in seconds. The method is developed for automatic assembly and it is based on the conditions that only one detail is handled at the same time, all details are ready for assembly at the assembly position and they can be handled by one person. The evaluation process is performed by simple rules which result in nine points for a good design, three points for an acceptable design and one point for an unwanted design. An assembly index is defined as the actual grade divided by the maximum possible grade.

The method contains two levels; a product level and a detail level, further described below. Questions concerning the total product are handled in the product level and detail related questions are treated in the detail level. Some of the subjects are already handled in the DFMA method described earlier.

Examples of the evaluation scores and DFA times are shown in Tables 31 and 32. It can be seen that the highest grade corresponds to the lowest assembly time. The result from the DFA2 analysis is an average detail score, i.e. a score for a whole product, as well as the score for a certain detail. Also an assembly index is calculated as the actual score divided by the maximum possible score. Finally, the number of parts and the minimum number of parts are shown.

Table 31 Grades concerning tolerance chains, from Rapp and von Axelson (2003).

Tolerance chains	Product
A tolerance chain is the sum of tolerances influencing the assembly process. Tolerance chains should be minimised in order to get a safer assemble process, not using subassemblies.	Point
No tolerance chains in assembly, only the tolerances of the parts themselves.	9 p
Tolerance chains for two parts exist in the assembly.	3 p
Tolerance chains for three or more parts exist in the assembly.	1 p

Table 32 Grades and assembly times concerning assembly movements, from Rapp and von Axelson (2003).

Assembly movements	Connections between details	
The fixation movement of a detail is faster for a simple motion	Point	DFA time
The assembly movement consists of a compression movement of one detail to be assembled.	9 p	0 s
The assembly movement consists of another movement than compression of one detail to be assembled.	3 p	0.5 s
The assembly movement consists of another movement than compression of several details at the same time.	1 p	0.8 s

Product Level

The subjects of the questions for the product level are presented shortly below:

Assembly directions: A product is preferred to only be assembled from one direction.

Base objects: An assembly should preferably start from a base object on which all other parts are assembled.

Designing base objects: The base object should be easy to handle and transport.

Parallel operations: Designers should aim for parallel operations.

Reduce the number of details: Keep the total number of details low, as well as the number of unique details.

Tolerance chains: Avoid tolerances depending on more than one part.

Unique details: Standard details are better to use than unique special details.

Detail Level

Below the subjects concerning detail level are described shortly:

Accessibility: Good access and space for assembly tools are required.

Adjustment: Avoid the need for adjustments in assembly and make the design fool proof.

Fastenings: The number of connections in a product should be minimised. Use simple movements. A special tool might be able to reduce the number of details.

Form: The form can be used for orientation, hinder rotation, be symmetrical or pronounced asymmetrical. Symmetry is measured in the same way as in the DFMA method described in Section 0.

Fragile details: Avoid fragile details as handling can harm parts.

Gravity centre: The gravity centre of a part should either provide stability or be pronounced eccentric.

Gripping: Design parts that are easy to grip, and try to make different details possible to grip in the same way.

Holding down: Fix details as soon as they are located.

Insertion: Avoid the need for exact positioning. Use large tolerances for insertion and use chamfers.

Integration: Try to combine parts using the criteria in Section 0 developed by Boothroyd *et al.* (2002).

Length: Long details should be avoided.

Movements in assembly: Use simple movements in assembly operations. Pressure is easiest followed by pulling and movement sideways. Rotation is the most time consuming assembly motion.

Orientation: It is advantageous if the orientation from manufacture of parts can be used in the assembly process, this way no reorientation will be needed.

Tangling: Parts should preferably be prevented from tangling.

Tolerances: Do not use smaller tolerances than necessary.

Turn around: Avoid operations that require turning the assembly over.

Weight: The weight of details should be kept to a minimum.

Analysis of Design Methods

In this chapter the design methods presented above are analysed and compared. Needs for improvement are discussed as well as the possibilities to adopt ideas from the methods into connection design in industrial construction. However, the chapter starts with discussing differences between building industry and manufacturing industry.

Building Industry *vs* Manufacturing Industry

In order to analyse the design methods it is important to point out the differences between manufacturing industry and building industry. Here, some of the differences are discussed.

For application in building industry the studied design methods must be adjusted due to size effects. The whole assembly will be larger when constructing a building. The assembly, and also the parts, is often much larger than the assembly workers. Further on, heavy parts are used in building industry, which demands lifting assistance such as cranes. The time needed for lifting and transportation has to be considered in another way for industrial construction as the handling time increases compared to manufacturing industry. Extra crane time is needed for elements that have to be moved a long distance. In some cases connections can be used as fixation points for lifting devices when elements should be lifted, see Section 0, which will affect both the elements and their connections. This is not considered in any of the design methods for manufacturing industry.

In manufacturing industry the final assembly is usually performed in a suited location. This is not the case in traditional building industry where the assembly is made at a new building site for each new project. Moreover, a product produced in manufacturing industry is often made in thousands copies. A building however is usually built in one or few copies. It is unusual to produce the same house in many copies or in many areas. A building system, on the other hand, can be used over and over again. Prototypes are often produced during development of a product in manufacturing industry. In building industry the prototype is commonly also the final product, especially if only one house of the same type is to be built. Connections in a building system can, on the other hand, be developed using prototypes of smaller parts or details. It is though important to stress the difference between connections used in a system with volume elements and a system with linear elements etc.

During traditional building design, it is common to perform the architectural work before the construction design. This leads to a late introduction of design methods, if such are used. However, the design work in manufacturing industry often starts using these methods. If the methods are used in building industry, design for assembly seems to be more important than design for manufacture. An assembly at a construction site is both time and cost consuming. The manufacturing of parts and details might be more important in manufacturing industry.

Symmetry can be hard to use in buildings as a wall cannot be made symmetrical upside-down or inside-out. Further on, a floor element is hard to design so that it can be assembled upside-down. On the other hand, symmetry can be used in smaller details such as bolts, dowels and other connection details which are commonly used in manufacturing industry.

Analysis and Needs for Improvement

In this section all methods presented above will be analysed. Parts of the methods that are useful for the building industry will be identified for further use. Also weaknesses of the methods are discussed. All methods will be commented separately below. Finally, possible starting points of the design work are discussed. But first all methods are compared and their characteristics are presented

Content of the Studied Methods

When evaluating design proposals there are two main types as described above; qualitative evaluation, which consider the ease for assembly relatively, and quantitative evaluation, which gives an estimated assembly time or cost. A method that gives the savings in time or cost for a certain improvement can be more favourable than a method that only ranks possible improvements. However, a quantitative method demands some sort of database with times or costs for all possible operations. There are also methods consisting of only guidelines. The methods studied are of all variants, as shown in Table 33.

Table 33 Compilation of the design methods described in Chapter 3.

Design Method	Guidelines	Qualitative Grade	Quantitative Time or Cost
Precast Concrete Industry	X	–	–
Boothroyd et al DFMA	X	–	X
Bralla DFA	X	–	–
Lucas DFA	–	X	–
Hitachi (AEM)	–	X	X
DFA(OS)	X	–	–
DFA2	X	X	X

Knowledge from the Precast Concrete Industry

The precast concrete industry has many relevant guidelines possible to use in connection design, for instance the ones concerning hook-up time, stability of elements, standardisation, handling damages and accessibility, see Section 0. However, it is important to note that the precast concrete industry is not a fully industrial construction method according to the definition of industrial construction used in this project. For example there exist guidelines for temporary supports, while the aim is to have a construction without them. Furthermore, methods like welding and grouting, which are possible to use in the precast concrete industry, should be excluded from the industrial construction process. This leads to harder demands on e.g. tolerances. A screw connection, or a snap fit connection, usually has a more narrow tolerance then a welded or grouted connection. A house built of precast concrete elements usually demands more supplementary work than a house build by totally industrialised elements. Another important aspect is the lack of a developed methodology, only guidelines are presented.

Design for Manufacture and Assembly®

The DFMA method developed by Boothroyd *et al.*, see Section 0, results in an estimation of assembly time depending on assembly difficulties; e.g. if the pieces to be assembled are small and tweezers have to be used. The methodology with handling codes might be possible to use in evaluation of structural connections, but then it has to be decided which parameters that these codes should be based on and how they should be graded. If an assumption of the time consumption or cost for an assembly is wanted, the codes have to be related to a database or time bank containing assembly times or costs for all possible assembly steps. The time needed to fasten a screw or a nut using different tools may vary a lot. Further on the time needed to put an element into position differs greatly depending on the connection type and size of element used. If the cost is to be estimated, many parameters have to be collected. Moreover, the cost is highly depended on the time used for assembly.

A data base with assembly times will be hard to accomplish since it has to be based on experiments or real building projects. Accordingly, a hard work has to be performed in order to create such a method. Nevertheless, it would be useful as the result is quantitative.

When a method should be developed for connection design, the size demands presented must be changed. A wall element, for example, is much larger than 2 or 20 mm. Instead it might be hard to handle parts smaller than, for instance, 20 mm if the assembly workers wear gloves. For large assemblies also the time for transports on the assembly site has to be considered. Transport distances might be longer and parts might be larger and heavier which influences the handling time. The database of assembly times is developed for small assemblies and will not give a correct approximation for an assembly of large parts.

Useful guidelines from the DFMA method are for example those handling the number of parts, access, simple fasteners and handling problems such as jamming and tangling. It is also important to locate parts before they are released which is discussed in the DFMA method. It is, on the other hand, irrelevant to use a guideline that recommends that the assembly should not be turned over, as this will never be a problem in a building process. Parts that are small, sharp and slippery are not very common in building industry, but it is however wise to avoid such details.

The method using criteria for part reduction is an effective tool for simplification of products. These criteria could be as useful in building industry as they are in manufacture industry.

Design for Assembly According to Bralla

The design for assembly method developed by Bralla has several guidelines similar to the design for manufacture and assembly method. There are no evaluation procedure in this method; only guidelines. Bralla discusses that it may be beneficial to add extra parts in order to ease the assembly. This can be difficult to combine with the criterion concerning part reduction, but it is however important to consider if adding an extra part may result in an easier assembly. Another guideline that can be of interest to use in building industry is to use fewer and larger fasteners rather than many smaller ones.

Lucas Design for Assembly Evaluation Method

This method considers the design efficiency in addition to handling and fitting of parts, which are handled separately. Both the handling and fitting ratios are simple to use and to compare between different design proposals. Also the design efficiency could be interesting in building industry. A method structured in this way should probably also suit structural connection design. The criteria must however be edited since they are developed to fit design in manufacturing industry; some criteria can be added and some can be removed or changed.

Hitachi Assemblability Evaluation Method

The Hitachi method is build up based on twenty elemental assembly tasks. If the method should be adjusted for connection design, these tasks have to be adjusted. A method structured this way is limited to the predefined assembly tasks which restrict the design proposals to connections only consisting of traditional assembly operations. New assembly types cannot be judged by such a method.

Design for Assembly (On-site)

The DFA(OS) method, developed by Lassl and Löfgren, consists mainly of guidelines. These guidelines are, on the other hand, well adapted to building industry. It is however important to develop an evaluation system so the guidelines can be used in an evaluation process.

Part reduction is also handled by this method. DFA(OS) uses the same part reduction method as both the design for manufacture and assembly method by Boothroyd and the design for assembly method by Bralla. This part reduction method is applicable in its present form also for building industry.

Design for Assembly 2

The structure of the method is good and easy to follow with the three levels of each criterion. It is however necessary to adjust the criteria to fit connection design in building industry. With the right type of questions the evaluation will show a good result regarding the qualitative evaluation. The quantitative part of the method, the assumed assembly time, has to be adjusted before it can be used in building industry.

Starting Point for Design

Before starting the design of a connection it is essential to decide which starting point to use for the design. Generally there exist two starting points, further described in the following text. Iteration is needed between these two extremes. In this way all demands are considered and a compromise is often the result. The two extremes are as follows:

Start with the connection: One approach is to start with the connection design. The idea is to make the connections as good as possible first and then continue with the design of the building system. In this case the connections will set the limitations of the elements and their design. It will for example decide how many connection points the element needs in order to resist the design load.

Start with the system: The other approach is to start with the building system design. When the system is decided the connections are designed to fit the demands. For example it can be decided that the element should have two connection points and that these connections must withstand the design load.

Connection Design Method

In the previous chapter the methods studied were analysed and possibilities to use them in connection design were discussed. Also the needs for improvement, in order to fit the building industry, were identified. With the knowledge from the analysed methods as a starting point, a method for connection design in industrial construction was developed which is presented in this chapter. But first, demands on a design method, considered during the development of the method, will be discussed.

Demands on Design Methods

A design method has to fulfil several demands. Below, desired properties for design methods are described followed by a presentation of functionality requirements for design methods.

Design Method Properties

Redford and Chal (1994) describes four properties relevant for a design method. These properties have been used as a starting-point during development of the new design method. A design method should be:

Complete: Many methods mostly have objective parts, while suggestions of how to improve an insufficient design are not given. However, design methods should be both objective and creative; they should both evaluate design proposals and give suggestions for improvements. Assembly problem areas should be brought to the users’ attention and the method should give the designer the opportunity to freely decide how to improve the design.

Systematic: It is important that all relevant information concerning a design proposal is handled in design methods. Therefore, step-by-step procedures that are systematic are preferred to be used.

Measurable: The method should give results that are of interest to designers. One central problem is to measure for instance assemblability in an objective way. It may be difficult to see how much a certain design costs as there are many design solutions possible, each one resulting in a specific time and cost. It is also important that it should be easy to compare different design alternatives.

User-friendly: Designers often have little time to learn new methods; they must therefore be easy to use. Furthermore, it must at the same time give reliable results. These two demands are contradictory to each other; the method might not be used if it is too complex and if it is too easy the quality and the accuracy of the result might be too low. It is also important that the method gives quick results.

Functionality Requirements

Huang (1996) describes ten functionality requirements set on design methods. The requirements are divided into two parts; the first part concerns basic functions which should be fulfilled and the second part concerns more advanced functions which are preferred to be fulfilled. The requirements according to Huang are as follows:

Basic Functions

- Gather and present facts.
- Measure performance.
- Evaluate if a product design is good enough.
- Compare design alternatives: Which design is better?
- Highlight strengths and weaknesses.

Advanced Functions

- Diagnose why an area is strong or weak.
- Point out how a design can be improved.
- Predict “what-if” effects.
- Carry out improvements.
- Allow iteration to take place.

A Four-Step Method for Connection Design

As a result of the analysis, a four-step design method has been developed, compiled in Appendix A. The design procedure is illustrated in Figure 46.

Each step will be further described is separate sections, but they will be introduced shortly in the following text. The design method starts with guidelines that are presented in order to provide the designer with background information of connection design in industrial construction. This background information is aimed to help the designer to develop industrial connections that are easy to assemble. Before continuing with the method, a description of the design proposal has to be added by the user. In the description, assumptions should be described in order to make it possible to later understand the choices made by the designer. The next step is absolute demands; if a connection should be evaluated it is important to first make sure that the connection fulfils its absolute demands. These demands have to be fulfilled in order to make the connection work properly, e.g. the load bearing capacity has to be fulfilled. The absolute demands are checked with help of a checklist. If the absolute demands are fulfilled the next step in the method is to evaluate how well the connection is suited for assembly. The evaluation concerns desirable demands; if these demands are neglected the assembly might be more difficult but the connection will still function correctly after assembly. The evaluation consists of criteria related to assembly which are divided into statements. The connection performance is graded depending on the chosen statement of each criterion. The result of the evaluation is an assembly index, which describes the connection’s assemblability relatively, and a list of which areas that can be improved. The improvement can either be a change of the connection itself or a change of the whole system. After the changes it is important to verify that the absolute demands still are fulfilled; the method should be used iteratively in the design process. When a connection has satisfactory result in the evaluation the next step can be performed; reduce the number of parts of the connection by eliminating unnecessary parts. The main reason for the part reduction is to make the assembly easer as fewer parts will result in an easier assembly. Besides, if a connection consists of fewer parts, it will probably be easier to manufacture. Then other aspects have to be considered as well; however these are out of scope for this project and are not treated in this report.

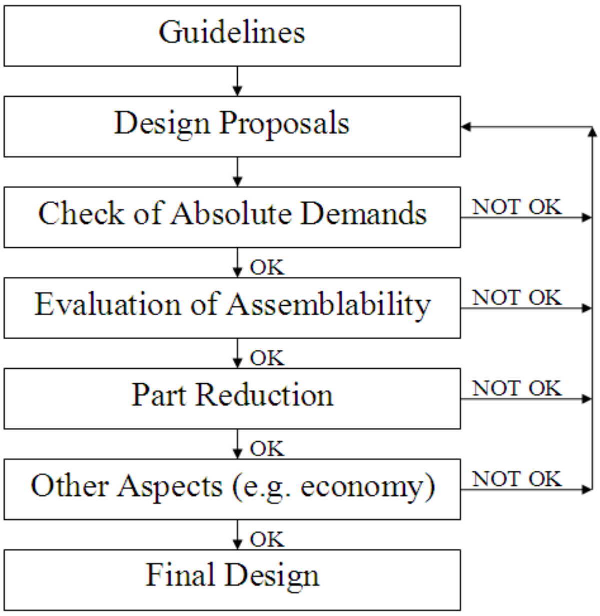


Figure 46 Design procedure for the developed method.

Guidelines for Structural Connection Design

In this section guidelines for connection design in industrial construction will be presented. The aim for the guidelines is to help the designer to develop new connections for industrial construction that are easy to assemble. Some of the guidelines are inspired by the methods in Chapter **Fel! Hittar inte referenskälla.** and some are general knowledge. Some of the guidelines will be further described and used in the evaluation, see Section 0.

Appearance: Connection details should not be visible in the final building if they are judged to reduce the esthetical value.

Construction environment: Production and assembly should be performed in a controlled and dry environment.

Costs: Element and their connections should be as cost effective as possible both regarding manufacture and assembly.

Crane time: The crane time needed for each element should be kept to a minimum.

Ergonomics: Production and assembly should be planned to improve the workers ergonomics.

Fixation methods: Only clean and dry fixation methods should be used and not connections methods such as welding and grouting.

Fixation: Connections should be easy to fixate by as few operations and assembly workers as possible.

Maintenance: Connections is preferred to be designed for a small need of maintenance. If maintenance is needed it should be easy to perform, e.g. regarding access.

Multipurpose connections: Connections are preferred to be used for other purposes than load bearing in the service state, e.g. used as lifting points during assembly.

Number of parts: The number of loose parts used in connections should be kept as low as possible.

Prefabrication grade: Elements are preferred to be fully prefabricated; no, or only little, supplementary work should be needed.

Stability: Elements should be stable as soon as possible.

Symmetry: Loose connection parts should be made as symmetrical as possible.

Temporary supports: Temporary supports should be avoided.

Tolerances: Connections' tolerances should be well adopted to their building system and easy to adjust.

Tools: The number of tools needed for assembly should be kept to a minimum. Large and heavy tools should be avoided.

Absolute Demands

It does not matter if a connection is easy to assemble if its absolute demands are not fulfilled. Thus it is important to check that all absolute demands are satisfied. These demands are however not the same for all connections. Depending on which type of structure and where in a structure the connection should be placed, the demands can vary significantly. For instance, demands concerning temperature and tightness might not be as important in a car park as it is in a residential building. For this reason, a product specific list, containing all absolute demands, has to be checked specifically for each situation.

In order to check the performance of possible connections a checklist has been developed, as introduced above. The checklist should be used to check that the connection fulfils its absolute demands. Three answers can be made for each demand; *Yes*, *No* or *Not relevant*. The three alternatives are chosen in order to make the checklist flexible so it can be used in different situations. An extract from the checklist is shown in Figure 47, while a total checklist is presented in Appendix A. This list can, however, be increased with other demands if needed. If all answers in the checklist are *Yes* or *Not relevant* the next step in the method can be carried out. If any demand in the checklist gets the answer *No* the connection can not be used and the designer must change the design of the connection, chose another design or consider to change the system.

CHECKLIST

If some of the relevant requirements are not fulfilled, these have to be fulfilled before the connection is possible to use. If all relevant requirements are fulfilled the connection studied can be rated using the evaluation method. Other requirements can be added if needed.

Does the connection studied fulfil the following requirements?

Is the connection…	**Yes**	**No**	**Not relevant**
able to resist applied shear force?			
able to resist applied tension force?			
able to resist applied compression force?			
able to resist applied bending moment?			
able to resist applied twisting moment?			
tight regarding sound?			
tight regarding air flow?			
tight regarding moisture?			
tight [illegible]arding [illegible]r?			

Figure 47 Extract from the checklist of absolute demands.

Assemblability Evaluation Method

The evaluation handles the assemblability of connections. The result should give the designer enough information about different connections in order to decide which connection is the most favourable in the actual situation. It shows which properties that could be improved in order to ease the assembly even more. The evaluation is based on criteria related to assembly. The evaluation do not present the result related to costs, but give an assembly index, which is a qualitative grade, on each studied connection. The evaluation can be seen in Appendix A, and in the following sections the structure of the evaluation and the criteria used in the evaluation will be presented.

Evaluation Structure

The evaluation is mainly inspired by the DFA2 method described in Section 0, but the criteria have been developed to suit connection design in building industry. The criteria are based on the guidelines and methods presented in this report and they are further discussed in the next section. Each criterion in the evaluation is given three statements at different levels; desired, acceptable and unacceptable. The designer should then decide which statement that is best suited for the studied connection. The number of statements has been limited to three in order to make the evaluation easy to use, as discussed in Section 0. Under the statements there are an empty box for adding comments and assumptions which justify the choice.

Each statement in the criterion is given a point, p, related to the level; 3 points (p_{max}) for desired, 1 point for acceptable and -1 point (p_{min}) for unacceptable. These points have been verified with the case study, further described in Chapter 0, and they are recommended not to be changed. The point range has been chosen in order to emphasize the difference in the statements, e.g. the negative point for the unacceptable statement (p_{min}) is chosen in order to emphasise the negativity. Furthermore, in order to weight the criteria to each other, every criterion are given an importance factor, I. The factor is set to one of three levels, depending on the relevance of each criterion; 0 for not relevant criteria, 1 for relevant criteria and 2 for extra important criteria. However, it is important to use the same factor for equal design situations in order to be able to compare different connections. It is also important to stress that the factors are based on the situation in which the connection should be placed. Finally, a grade, G, is calculated for each criterion as the importance factor times the point of the criterion, see Equation 9.

$$G = I \cdot p \tag{9}$$

The result of the evaluation is shown both for each criterion separately and for the studied connection as a whole. On the result page a summation with importance, point and grade for each criterion is presented in order to give the user an overview. The negative grades are marked red in order to get the users attention and highlight the criteria that can be improved. In addition, criteria with good grades are marked green. The number of criteria used (criteria with importance factor 1 or 2) are also presented. For the studied connection a mean grade, G_{mean}, and an assembly index, A, are calculated. The mean grade is calculated as the sum of the criteria grades divided by the sum of the importance factors, see Equation 10. Of course, the calculation could be made by dividing the sum of the criteria grades by the number of questions. However, the chosen calculation is made in order to take the importance into account and it results in a mean value between -1 (p_{min}) and 3 (p_{max}). The assembly index is calculated as the quotient of the mean grade minus the minimum point and the maximum point minus the minimum point, see Equation 11. The assembly index is presented in percent with the best value of 100 % and the lowest of 0 %. The connections can then be compared to see which connection had the best assembly index. The designer can then choose which connection to use or make changes in design and start over checking absolute demands and redo the evaluation.

$$G_{mean} = \frac{\sum G}{\sum I} \tag{10}$$

$$A = \frac{G_{mean} - p_{\min}}{p_{\max} - p_{\min}} \tag{11}$$

The evaluation is preferred to be performed in an Excel-document where all the equations are included in the file. The grade for each criterion will than be calculated automatically. Warnings for errors are included in the file. There are warnings if more then one statement are chosen, shown in Figure 48, and if no statement is chosen, shown in Figure 49.

Positioning of Elements	IMPORTANCE: 1	
Elements should preferably be guided into their final position.		
STATEMENTS	**CHOICE**	**GRADE**
The connection guides elements into position	x	1
The connection partly guides elements into position, e.g. self guiding in one direction	x	
The connection provides no self guiding for elements		
Comments and assumptions:		
MORE THAN ONE CHOICE MADE		

Figure 48 Warning in the evaluation; more than one choice are made.

Stability	IMPORTANCE: 1	
Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		
Comments and assumptions:		
MAKE A CHOICE		

Figure 49 Warning in the evaluation; no choice are made.

Evaluation Criteria

In this section the criteria used in the evaluation will be presented. Each criterion is discussed separately and choices are explained. The purpose is to give an understanding of the criteria and why those have been chosen. Some of the criteria have been mentioned above but here they will be presented more in detail.

Stability

For industrial construction, temporary supports should be avoided as long as possible. This is an extension of the guideline for precast concrete, Section 0, where temporary supports are allowed but should be prepared. Each element should preferably be stable as soon as it is put in position. The connections used to hold an element in place could for instance be made moment resistant to avoid the need for extra supports. However, the connections might be more complex and require even more time for assembly than the time used for temporary supports. The connection might also be more expensive to manufacture. The most desirable connection should eliminate the need for temporary supports but not be too complex to manufacture or to assemble. To achieve this, the designer has to perform a manufacture analysis. Stability is important regarding crane time, which should be kept to a minimum. For that reason, stability at once has been decided as the optimal solution. If the element is stable after a small fixation or adjustment it is acceptable, but if major fixation operations or temporary supports are needed the lowest point will be given.

Positioning of Elements

In order to make the assembly easier, connections are preferred to self-guide elements into their final position, which is discussed in Section 0. Self guiding refers to the connections ability to self align and self locate elements. This is extra important if the precision of the lifting devise is not very exact. This is also important regarding working environment. A connection that guides an element into position is the best solution and no self guiding is the worst solution. Connections that are partly self guiding, e.g. guide an element only in one direction, are given the mean point.

Positioning of Loose Parts

Also loose connection details should be self guiding as these should be assembled to the connection. A connection can exist of several loose details, if all these are self guiding the highest point is given. If some loose details are self guiding it is acceptable and if no self guiding is provided the lowest point will be set.

Number of loose parts

Many connection are designed containing lose parts, such as pins and bolts. Handling of loose parts can be time consuming; therefore the loose connection parts needed during assembly should be as few as possible. To be able to evaluate connection types correctly, subassemblies are defined as one part. One subassembly can be a threaded rod with two bolts delivered to the assembly site in one piece. Since most connections have at least one loose part, one or no loose parts have been defined as the best solution. Moreover, connections containing two or three loose parts are given the mean point and connections including more than three loose parts are given the lowest point in the evaluation.

Size of Loose Parts

As mentioned above handling of loose parts can be time consuming. As well as the number of loose parts, the geometry of these parts is important. Long or wide loose parts that are hard to handle should be avoided. With help of the DFMA method described in Section 0, an estimation of size intervals has been made for building industry. A part between two and thirty centimetres is graded highest while a length between one and two centimetres or thirty to a fifty centimetres is on an acceptable level. However, sizes under one centimetre and parts over fifty centimetres are hard to handle, therefore treated as unacceptable in the evaluation.

Weight of Loose Parts

Also the weight of loose parts has to be considered. Too heavy parts result in a more difficult assembly. Here weights below one kg are valued highest and weights between one and three kg are considered acceptable while weights over three kg are chosen to get the lowest point. The estimations of weight intervals have been based on experiences.

Need for Assembly Workers

In industrial construction the assembly work should preferably be possible to perform by workers without special skills. Special skills are in this project defined as welding skills or similar. Of course all assembly workers have to know how to assemble the system. Furthermore, the number of assembly workers should be minimised. Every operation should preferably be performed by only one worker. The number of workers is defined as the number of workers in addition to the crane operator. If an assembly can be performed by only one worker with no special skills the highest point will be given. If two workers without special skills are needed it is acceptable in the evaluation. Finally, a need of more than two workers or workers with special skills is under the acceptable level.

Safety for Workers

In addition to the number of assembly workers, the evaluation treats safety for the assembly workers. The risk for workers getting injured in an assembly process should be minimised. In this evaluation only injuries related to the connections are considered. In the evaluation connections are judged depending on the risk workers are exposed to while performing an assembly.

Tools

At the construction site, or assembly site, operations are performed in different locations. If ungainly tools are needed, the assembly operation and movement of these tools will be difficult. Equipment that needs extra power sources, e.g. air tools, should be avoided as long as such do not reduce assembly time remarkably. The designer has to consider whether the time reduction for a curtain tool is sufficient or not. Further on, it is also beneficial that the number of tools needed is kept to a minimum. Therefore the optimal solution is if not more than one small tool is needed. If two or three small tools are needed it is acceptable while a need for many small tools or heavy, large or ungainly tools are under the level of acceptance.

Accessibility

During assembly it is important that connections are accessible for the workers. It should be avoided to place connections in tight sections or outside the building at high levels, in order to improve the workers ergonomics. It is also considered if a connection has to be handled from more than one side. If the access is restricted there is a risk for lacking quality. Therefore, handling needed from one side only with easy access is the optimal solution. Easy access with handling needed from two sides is considered to be acceptable while restricted access or handling needed from more than two sides is under the acceptable level.

Fixation Method

Fasteners should be designed as simple as possible. In industrial construction no unclean fixation methods, such as welding and grouting, are acceptable. Therefore such fixation methods must get the lowest point in the evaluation. On the other hand, snap fits that lock the connection instantly or fixation with a simple motion are considered to be the best fixation method. Fasteners consisting of screws or a combination of motions are in the evaluation considered to be acceptable, giving the mean point.

Protruding Parts

When handling an element during assembly it is important that its connections do not damage components, protruding parts, connections or personnel. Connections which could be damaged have to be protected. This can be accomplished by making the exposed details less fragile or by protecting them in some way. The best solution is a connection which is not harmful to elements or fragile itself. If damage is possible it is important to define how large the damage is. Of course, a damage that is easy to repair is better then a damage that is difficult to repair or that require exchange of a whole element. Yet, a connection that is harmful or fragile is not a desired solution in industrial construction.

Multi-Purpose Connections

Connections used for more than its main purpose, called multi purpose connections, can increase the efficiency of an assembly. One application, useful for the assembly process, is integrated lifting devices in the connections which are treated in the evaluation and discussed above. Additionally, it is important that the elements hang straight when lifted. The best solution needs no changes to serve as lifting devise while a connection that serves as a lifting device with help of some extra equipment is acceptable. If the connection does not serve as lifting device the connection gets the lowest point.

Fool Proof

Connections should be hard to misassemble. Parts should, for example, only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose. As a result, correctly designed connections will decrease the number of possible errors during assembly. Therefore, a connection easily misassembled is rated under the acceptable level. Connections with some actions made to prevent misassembly are acceptable while connections impossible to misassemble are given the highest point in the evaluation.

Demountability

The environmental effects are important to handle in industrial construction. Buildings should rather be disassembled then demolished after service life. As a result, a disassembled building can be recycled or reused. It can also be necessary to replace an element during service life. Furthermore, the ability for disassembly depends to a large amount on the connections of the elements. A connection is considered to be best if disassembly is possible without causing damage to elements or connections themselves. Disassembly causing damage to connections but not to elements is acceptable in the evaluation. However, if only demolishment is possible it is under the acceptable level.

Tolerance

As discussed in previous chapters, tolerances are an extensive question in industrial construction as well as in any construction. It is hard to define tolerances in exact numbers as it depends on the system. In order to be able to use the evaluation for different systems the criteria refers to the ease to adjust after set tolerance limits. Therefore, connections that adjust automatically when assembled are desired. Connections easy to adjust are acceptable while connections hard to adjust or require extra time is unacceptable.

Minimising the Number of Parts

When the previous steps in the method are performed and the designer has decided which connection to use, the final step can be carried out. The purpose of this step is to eliminate all unnecessary parts in the chosen design in order to make it even easier to assemble. The method used to reduce parts is the one developed by Boothroyd *et al.* The same method is also used by Lassl and Löfgren (2006). The questions for part reduction are for convenience repeated here. If a connection part gives negative answer to all of the three following questions it could be combined with another part.

- Does the part move relative all other parts?
- Must the part be of another material than other parts?
- Must the part be separated from other parts, or else one or more of the other parts' assembly will be impossible?

An example of a part reduction with help of these questions is shown below. The example was first presented by Lassl and Löfgren (2006). In Figure 50 and Table 34, an example of a connection is presented. The connection intends to connect a wall element to a column; it will however not be further described in its context. The three questions are then answered for each part and the ones that are able to combine or eliminate will be identified. The connection after part reduction is shown in Figure 51 and Table 35 and it can be seen that the connection is simplified and have fewer parts.

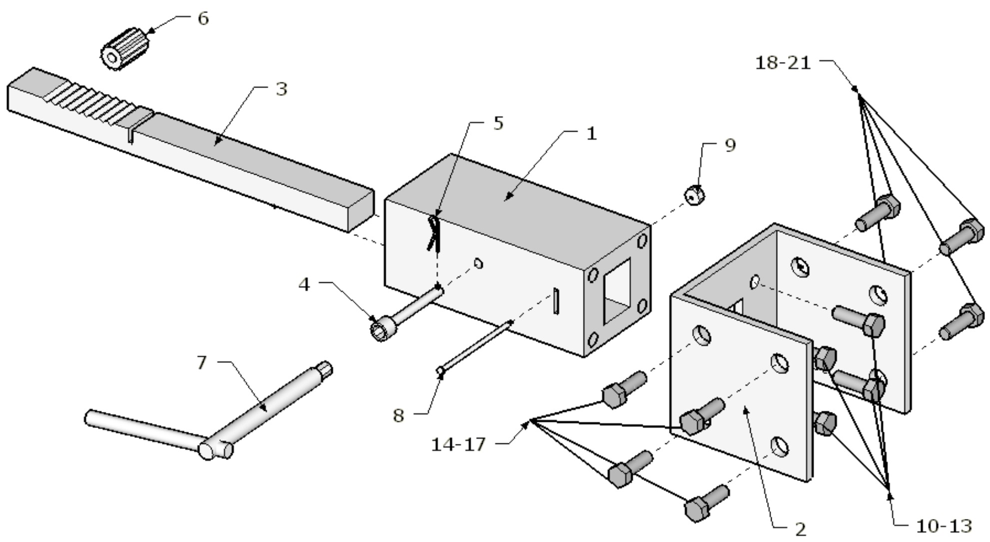


Figure 50 Example of a connection before part reduction, Lassl and Löfgren (2006).

Table 34 Description of the parts used in Figure ***Fel! Hittar inte referenskälla.****.*

Part #	Part description
1	Stock tube, main container
2	Mounting plate
3	Revolver
4	Rotating axis
5	Wedge (locks 4&6 in place)
6	Gearwheel (mounted on part 4)
7	Handle (inserted into 4)
8	Screw (locks revolver)
9	Nut (mounted on revolver)
10-13	Screws (fastening mounting plate on stock tube)
14-17	Screws (fastening mounting plate on wall element)
18-21	Screws (fastening mounting plate on wall element)

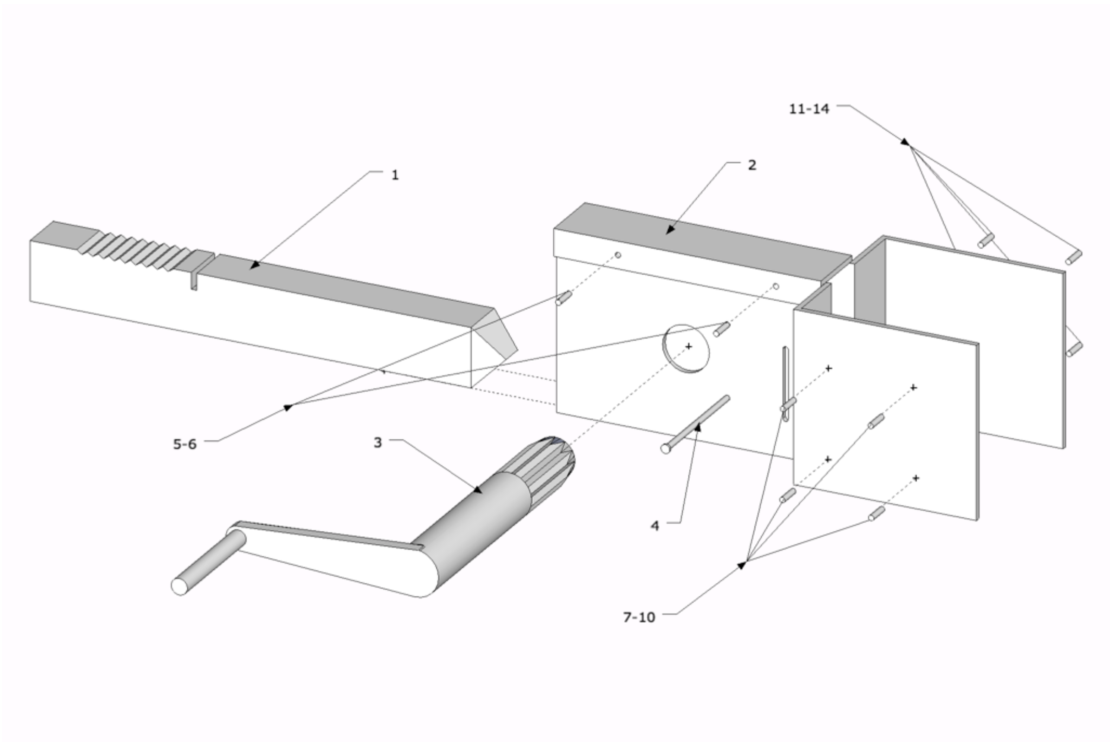


Figure 51 Example of the connection after part reduction is performed, Lassl and Löfgren (2006).

Table 35 Description of the parts used in Figure ***Fel! Hittar inte referenskälla.****.*

Part #	Part description
1	Revolver
2	Sheet metal box
3	Handle with cogs
4	Plastic snap fit plug
5-6	Rivets (holding the box together)
7-10	Rivets (fastening the box on wall element)
11-14	Rivets (fastening the box on wall element)

Other Aspects

Several other aspects, besides assembly, have to be considered before a final design is chosen. Manufacture, accessible material resources, overall economy, durability, partnering organisations and producers are examples of such aspects. In Figure 52 design for assembly is shown as one of several areas that all influence the design of structural connections in industrial construction. These aspects are not considered in this project but they are however important to take into consideration when designing connections.

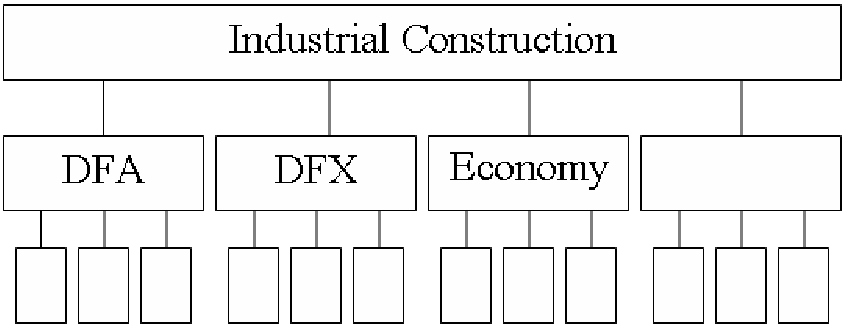


Figure 52 Assembly is one area besides for example manufacture and economy that all are a part of industrial construction.

Case Study

A case study has been performed in order to improve and test the evaluation step of the design method during its development. Several connections were tested in the study. There was no interest to improve the connections themselves but the case study was aimed to check, calibrate and improve the evaluation method only. Different versions of the evaluation method have been tested resulting in the final evaluation method described in Section 0.

This chapter starts with a presentation of the connections tested in the case study including their assumptions. This is followed by a presentation of criteria which have been rejected from the method during the case study. The rejected criteria can still be seen as guidelines when designing structural connections. Finally, results from the case study will be presented and discussed. The result presentation will include results from the final method only. However, tested point ranges and different importance factors will be discussed.

Connections Evaluated

Several connections of different types were tested. The connections used in the case study are described below with figures, explanations and assumptions. The purpose is to give a quick overview and not to give full knowledge of each connection. All connections presented have been evaluated using the different versions of the evaluation method during its development and the results were compared. Some of the connections studied are industrial connections while others are not at all industrial. The different grades of industrialisation were chosen in order to see if different connections gave expected varying results. The connections were iteratively tested in order to see the result changes for different changes in the method.

Consolis Floor-to-Floor Connection

The connection is used between concrete elements in a building system developed by Consolis (2007), see Figure 53. The connection in the study is a floor-to-floor connection but the same connection can also be used for wall-to-wall connection, this situation is however not treated in the study. Each connection consists of steel plates cast into the elements where the connection is located. The connection is locked by a treaded bar and two nuts fixating these steel plates. To ease the assembly the bar and the bolts are assumed to be preassembled; delivered to the assembly site as one part. It is also assumed that this connection is not used as a point for lifting as other connections in the same element are more suitable for connecting a lifting devise.

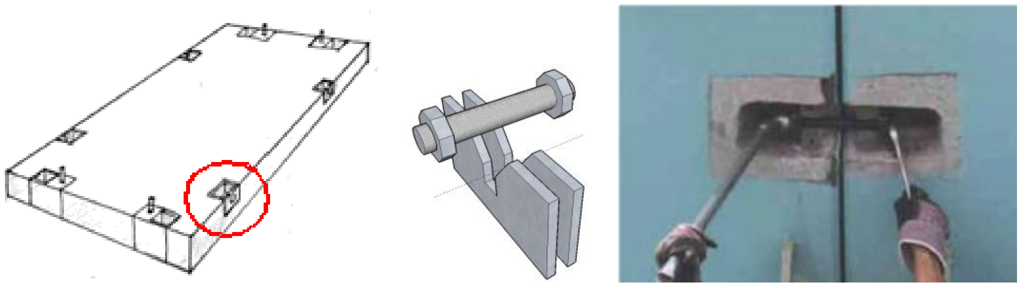


Figure 53 Floor-to-floor connection for concrete elements, Consolis (2007).

Consolis Wall-to-Floor Connection

This connection, shown in Figure 54, comes from the same system as the floor-to-floor connection above developed by Consolis (2007). This connection is used both when a wall element is placed on top of a floor element and when a floor element is placed on top of a wall element. However, the study only handles the second of these cases. The connection consists of a steel box that is cast into concrete elements in a factory. A bolt from one of the steel boxes in an element underneath is fixed with a nut in the steel box in the element above. This connection is assumed to serve as a lifting point if a bolt is placed on the rod.

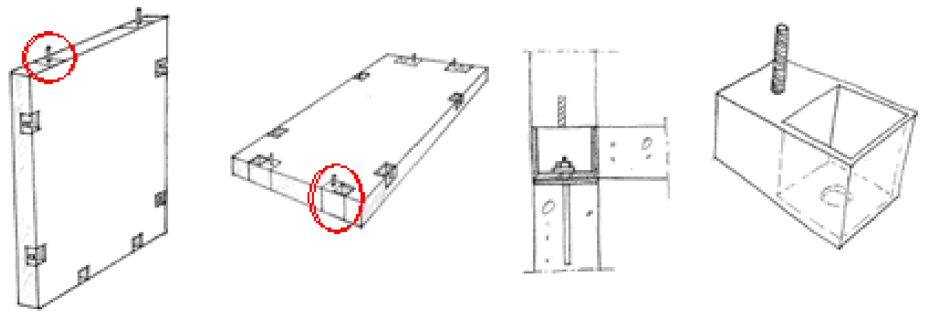


Figure 54 Connection used to connect floor elements to wall elements, Consolis (2007).

Concrete Beam-to-Column Connection

The beam-to-column connection, shown in Figure 55, is used for prefabricated concrete elements and is adopted from Betongvaruindustrin (2005). The beam is slipped on to a treaded rod that is precast into the column. On the topside of the beam the connection is fixed with a nut. The hole in the beam is assumed not to be filled with concrete which is a possibility.

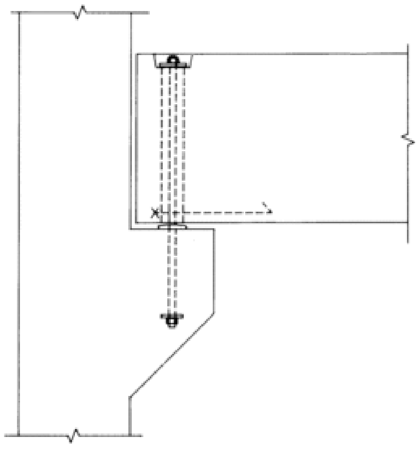


Figure 55 Prefabricated concrete beam and column connected with a bolt, adopted from Betongvaruindustrin (2005).

Steel Beam-to-Column Connection

The connection consists of standard hot-rolled steel beams fixed together with nuts and bolts, see Figure 56. The connection is adopted from SBI (1988). A steel plate with predrilled holes is welded to the end of the horizontal beams in a factory. Also the vertical beam have predrilled holes were the horizontal beam is to be fastened.

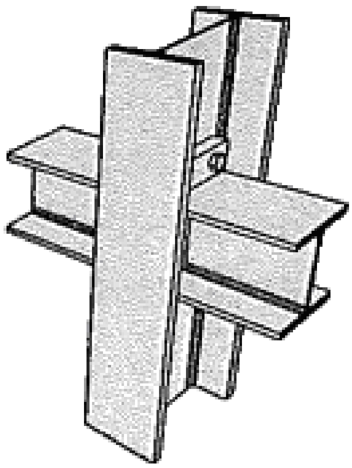


Figure 56 Bolted hot rolled steel beams, adopted from SBI (1988).

Concrete Cast in-situ Connection

This connection is a joint between prefabricated concrete floor elements and a prefabricated concrete wall or beam, see Figure 57. Extra reinforcement bars are added and concrete is cast in situ in order to make the connection fixed. No extra supports are assumed to be needed before the concrete is cast.

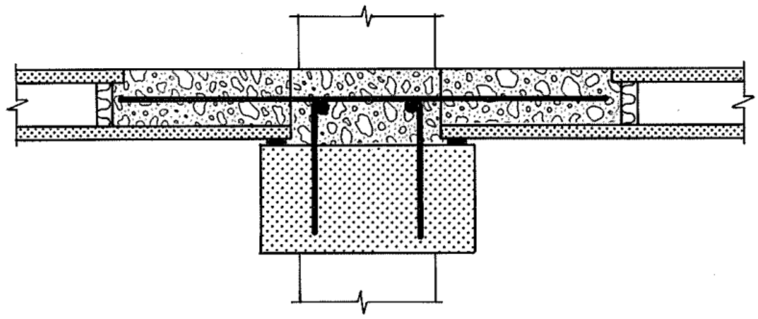


Figure 57 Connection for prefabricated concrete elements, connecting two floor elements upon a beam, from FIP (1988).

Beam with Movable Steel Plate

The connection consists of a beam hooked to a column with help of a movable steel plate, see Figure 58. The connection is developed by Spenncon AS and is published in *fib* (2007). The connection is assumed to be made of steel cast into concrete elements. It is supposed that the hook is easy to slide horizontally without any need for tools. The purpose with the movable hook is the possibility to lift the beam in place before sliding out the hook into the column which decreases the risk of jamming and damage of the connection detail.

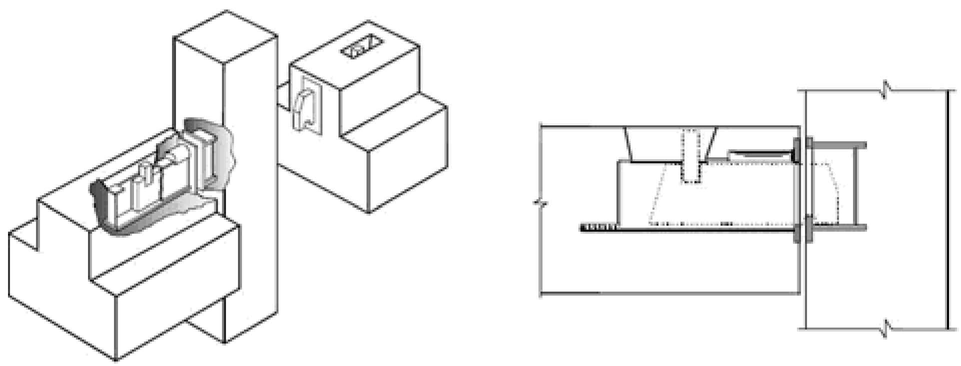


Figure 58 Movable steel plate connecting a beam to a column, published in fib (2007).

Welded Connection of Steel Beams

A welded connection of two hot-rolled steel beams is shown in Figure 59. The plate between the beam ends is assumed to be welded to one of the beams in a factory and only needs to be welded to the other beam on site. Welding require workers with special skills. With rightfully preformed welds, the connection will be very stiff. The assembly of the connection is however weather sensitive; rain and wind can be harmful.

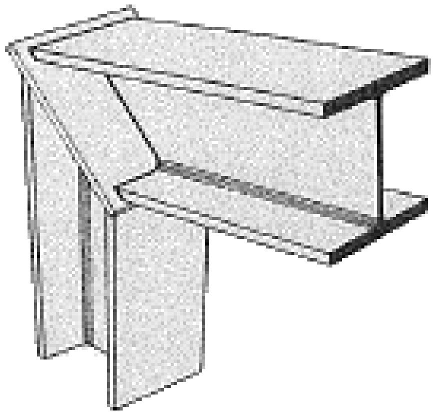


Figure 59 Steel beams connected by welds, adopted from SBI (1988).

Timber Connection with Dowels

This timber connection consists of two timber members joined together with steel dowels, see Figure 60. There is also a plate inserted in the connection through which the dowels are placed. The plate increases the stiffness of the connection which can be a problem in wood connections.

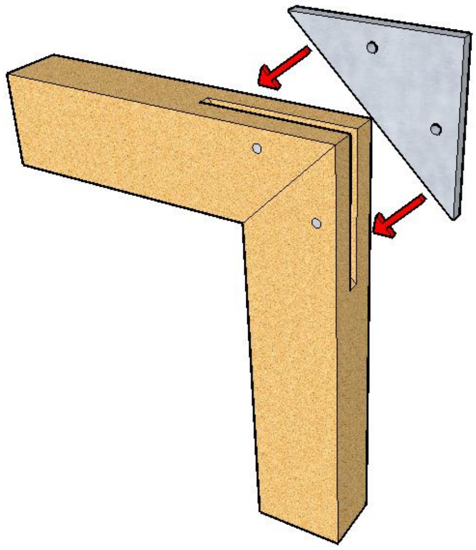


Figure 60 Timber connection with steel dowels.

Roller Bearing for Volume Elements

The connection, shown in Figure 61, is used between volume elements, and is developed by Setra Group (2007). The connection consists of three parts; a cylinder which is loose and two other details which are attached to the elements in a factory. At the assembly site the cylinder is placed on the lower element just before the next element is put in place. The connection cannot resist tension in the vertical direction but it is assumed to be stable thanks to the self weight of the elements above. If not, the tensile forces have to be resisted in another way.

Figure 61 Roller connection for volume elements, adopted from Setra Group (2007).

Connection for Storage Rack

In Figure 62 a storage rack is shown. The connection studied is where the beam is attached to the column shown in the figure. There are holes in the column into which the beam can be hooked on to. The only tool assumed to be used is a hammer.

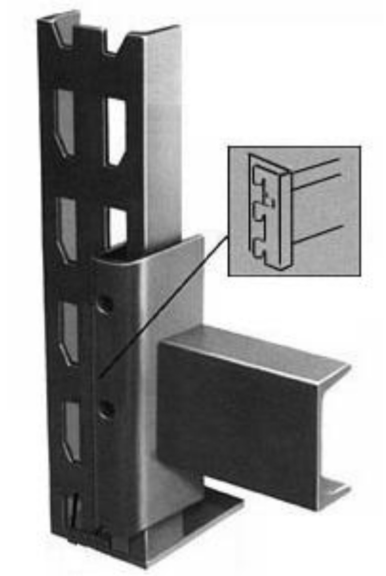


Figure 62 Connection of beam and column in a steel storage rack, Jarke (2007)

Beam Shoe

The connection detail is used when fastening a timber beam to a wall or a column. It consists of a bent steel plate fixed using nails, see Figure 63. It is assumed that the beam shoe is already fastened to the wall or column before the timber beam is lifted in place.

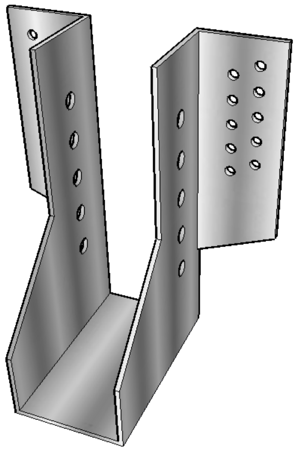


Figure 63 A beam shoe used to connect a timber beam to a wall or a column.

Results

As described above, all connections have been tested during the development of the evaluation method and the case study has been performed in order to check, calibrate and improve the design method only. In this section, results from the final evaluation method will be presented and discussed. The results from previous versions will not be presented in the thesis. Motivations for the structure and the grading system will however be included.

Result Presentation

The results for each connection are presented in Table 36 (for the total case study, see Jürisoo and Staaf, 2007). In the table, it can be seen that a connection with low prefabrication grade or with a complex assembly gets a low assembly index. The concrete cast in-situ connection, for example, which is quite complex to assemble, gets an assembly index of 16 %. The roller bearing connection for volume elements gets, on the other hand, an assembly index of 88 %. All other connection handled in the case study get assembly indexes scattered between these values. The results represent the ease of assembly in a realistic manner as good designs were given a good result and vice versa. This indicates that the most important areas regarding assembly are handled in the evaluation. It is however important to stress that the connections in the table should not be compared to each other as they are used in different situations. When two or more connections should be compared, it is critical that they are evaluated in the same location in the system and have the same importance factors of the criteria. Only then can the connections be compared. This is the case for all beam-to-column connections as they are, due to the same situation, given the same importance factors.

Table 36 Summation of the results from the case study of the final evaluation method.

RESULT FROM CASE STUDY	Consolis Floor-to-Floor Connection	Consolis Wall-to-Floor Connection	Concrete Beam-Column Connection	Steel Beam-to-Column Connection	Concrete Cast in-situ Connection	Beam with Movable Steel Plate	Welded Connection of Steel Beams	Timber Connection with Dowels	Roller Bearing for Volume Elements	Connection for Storage Rack	Beam Shoe
Number of Criteria Used	13	16	16	16	15	13	13	16	16	13	16
Mean Grade	2,33	1,45	1,45	1,09	-0,37	2,47	-0,26	1,13	2,53	1,77	1,09
Index	83%	61%	61%	52%	16%	87%	18%	53%	88%	69%	52%
Stability	-	3	3	1	3	1	-1	-1	3	1	3
Positioning of Elements	-	-2	-2	-2	-1	2	-2	-1	6	1	-2
Positioning of Loose Parts	3	-1	-1	-1	-1	-	-	-1	3	-	-1
Number of Loose Parts	3	2	2	-2	-1	6	6	1	3	3	-2
Size of Loose Parts	3	3	3	3	-1	-	-	3	3	-	3
Weight of Loose Parts	3	3	3	3	1	-	-	3	1	-	3
Need for Assembly Workers	3	6	6	6	-2	6	-2	3	3	3	6
Safety for Workers	1	1	1	1	-1	3	-1	3	1	1	1
Tools	2	6	6	2	-2	6	-2	3	3	3	6
Accessibility	3	3	3	1	-1	3	-1	1	3	3	1
Fixation Method	2	2	2	2	-2	6	-2	1	3	1	2
Protruding Parts	3	-2	-2	6	2	6	2	3	3	3	2
Multi-Purpose Connections	-	1	-1	-1	-	-1	-1	-1	-1	-1	-1
Fool Proof	3	1	3	1	-1	3	-1	1	3	1	1
Demountability	3	3	3	3	-1	3	-1	1	3	3	1
Tolerance	3	3	3	1	1	3	1	-1	3	1	1

Further on, the table shows which areas (criteria) that get low grades and therefore have to be considered in a redesign, if a connection should be improved. Also good results are highlighted in the summation. For all criteria, varying statements are chosen for the tested connections, which confirm the accuracy of the criteria. Some criteria in the early versions of the evaluation gave the same result for all studied connections. These criteria were, partly for this reason, rejected from the evaluation method. They are however described in the next section. As can be seen in the table, the criteria concerning multi-purpose connections get the same result for most of the studied connection. However, this due to the amount of non-industrial connections in the case study and the criteria is still judged as important to keep in the evaluation.

There are totally sixteen criteria in the final evaluation method. There were at the most three criteria that were considered not to be relevant for the studied connections. The criteria handling loose parts were irrelevant for the connections that did not consist of any loose parts. They were on the other hand relevant for the other connections. All criteria were however relevant for most of the connections. None of the criteria were irrelevant for more than three of the eleven studied connections.

Structure and Grading

The structure of the evaluation method is, as mentioned before, inspired by the DFA2 method which is based on criteria handling several assembly areas. This structure was chosen because it is simple and systematic and easy both to follow and to use. The other studied methods are based on assembly operations and their time consumption and cost. If such a method should be developed for structural connections in building industry, all relevant operations has to be identified and given an assembly time and cost.

In the evaluation method described earlier in this report, importance factors are used to balance the criteria. Several different importance factors have been tested during development of the evaluation method. In the first versions of the method, no factors were used. It was however decided that all different criteria were not equally important in every situation, so a system using importance factors were introduced. With help of the importance factors the magnitude of each criterion could be decided. When importance factors were introduced in the method, it was possible to set factors from zero, for not relevant, up to three, for very important criteria. It showed however that the highest factor, the factor three, gave a too large impact on the result of the evaluation. Because of this lack of balance in the evaluation, the importance factor three was removed. As an extra result of this the importance factors became easier to choose, as only three options remained; irrelevant, relevant and extra important. If the importance factor two is chosen for a criterion, the criterion will affect the result twice as much as it would with a factor one. This means that if all sixteen criteria are relevant, i.e. given the importance factor one, each criterion will affect the result by one sixteenth. However, if one of the criteria is given the importance factor two, this criterion will affect the result by two seventeenth and all other criteria affects the result by one seventeenth.

Also the criteria points, given for each statement, have been tested in the case study. In the DFA2 method, a point scale of 1, 3 and 9 was used. This was considered for the new method as well, however, the negative point for unacceptable statements was considered more important as it stresses the negative effect of the statement. Therefore, in the first evaluation version the point scale minus one, one and four were used. These points appeared to give quite good results except for the highest point. Point four appeared to affect the result too much. So, only the highest point was changed from four to three. This resulted in criteria points set to minus one point for unacceptable, one point for acceptable and three points for a desirable solution.

Criteria and Guidelines Rejected from the Evaluation

As discussed above, it is important that the method is user-friendly and that it is not too extensive. Therefore irrelevant criteria should be avoided. Here are some criteria described that were rejected during the case study.

Symmetry

Many of the methods studied recommend symmetrical parts. In building industry, however, most elements are asymmetrical in order to fit their position in the final product. An external wall is, as discussed in Section 0, of course not equal on the inside and on the outside. On the other hand, symmetry can be favourable for connection details such as pins and dowels. But if details like these are used they are always symmetrical in some extent. Further on a whole connection can be symmetrical which off course is favourable. This is however more important when an element should be produced, as the same connection could be mounted in different directions and positions.

Sticky, Slippery etc

The case study resulted in that no connections were sticky, slippery or hot. As all studied connections gave the same result this criteria were rejected. This was done in order to keep the number of criteria low as this will ease the use of the evaluation. Some of the ideas from this subject were instead treated in the criterion concerning protruding parts and damage.

Special Tools

During development of the method it was first decided that special tools should be avoided. But later it was determined that such tools could be favourable if these reduces the assembly time. The tools should however not be ungainly to use or move on the assembly site.

Unintended Disassembly

In industrial construction, connections might be possible to demount. Connections must however be designed to eliminate the risk of being demounted, by e.g. a user, during service life. This was first handled in a criterion in the evaluation method but during the case study the subject was however decided to be handled in the checklist for absolute demands. As an unintended disassembly would be devastating, this cannot be treated as a desired property.

Tolerances

In the evaluation method tolerance is graded depending on the connections ease to adjust within its tolerance range. It has been considered to instead grade tolerance on the basis of tolerance intervals. A connections tolerance interval is however decided depending on its system and it is therefore necessary to fulfil the prescribed tolerance. So, fore this reason, the control of tolerance interval is performed in the checklist for absolute requirements while the ease for assembly depending on a connections tolerance is handled in the evaluation method.

Conclusions from the DFA study

In this chapter conclusions of the DFA study are drawn. This is followed by a comparison of the result and the aim of the project. Finally, suggestions for further studies are presented.

Conclusions of the method development

There are both differences and similarities between manufacturing industry and building industry. The methods used in manufacturing industry are focused on assembly of small details in a suited workstation. Many guidelines could however be adjusted into the developed method for connection design in industrial construction. The new method works as intended for evaluation and control of structural connections, according to the case study presented above. It gives a relative grade and an assembly index for each connection and troublesome areas in a studied design are highlighted. It is possible to ease the assembly by improving both the connection itself and the building system. The method does however not give a time or cost estimation which could be useful. So if this is wanted, the method has to be further developed.

In the evaluation sixteen criteria were used. In the case study it was shown that at the most three of these were considered not to be relevant of the studied connections. All criteria were however relevant for most of the connections. None of the criteria were irrelevant for more than three of the eleven studied connections.

In the evaluation, some of the criteria are exact and precise while others handles personal opinions. It is easy to choose the correct statement of the exact criteria but the evaluative ones can be more troublesome. Different designers might have different opinions concerning a certain connection or design aspects, therefore different choices can be made. It is therefore important to evaluate well defined connections in order to get a reliable result. The statements can also be apprehended individually by the designer. This is prevented by providing the possibility to write assumptions and motivations for the choice of statement. The most comparable results are however achieved if the same designer fills in the evaluation form for all connection that should be compared. The evaluation has been tested by experienced designers, and the results were the same for most criteria. When the results differed, this turned out to mostly be due to different apprehensions of the studied connection.

In the design method, all absolute demands have to be fulfilled if a connection should be possible to use. All absolute demands are however not always possible to fulfil; compromises might be necessary. The designer has to decide if it is possible to change the building system in order to make the absolute demands easier to fulfil.

Check of Huang's Functional Requirements

Most of the functional requirements presented are fulfilled by the design method, which can be seen in Table 37. All information concerning the studied connections is collected in the connection information page in the evaluation. The assembly performance is measured by choosing statements. Whether or not a design is good enough is not directly determined by the method as the assembly index varies for different connection types. However, it is possible to use the result as a decision basis when deciding if a connection is good enough. Furthermore, it is possible to compare design alternatives which are aimed for the same building system and have the same function. Strengths and weaknesses are pointed out in the result page of the evaluation; good areas are marked green and problem areas are marked red. By controlling the statements for each criterion it is possible to see why an area is strong or weak and improvements can be performed in order to achieve the best statement. It is also possible to see how the assembly index changes for a certain redesign, but the choice of statement in the modified criteria has to be changed in order to see the effect. The method does not carry out improvements by itself but an iterative evaluation procedure can be used for design changes.

Table 37 Summation of the fulfilment of the requirements on a design method, which are presented in Section 0.

Basic Functions	Fulfilled	Not Fulfilled
Gather and present facts	X	
Measure performance	X	
Evaluate if a product design is good enough	X	
Compare design alternatives: Which design is better?	X	
Highlight strengths and weaknesses	X	
Advanced Functions	**Fulfilled**	**Not Fulfilled**
Diagnose why an area is strong or weak	X	
Point out how a design can be improved	X	
Predict “what-if” effects	X	
Carry out improvements		X
Allow iteration to take place	X	

Aim Verification

In the project several design methods used in manufacturing industry have been studied. The methods have been analysed in order to see if they are possible to use for connection design in industrial construction. Areas which could be used and areas which are not relevant for industrial construction were identified and discussed. The differences between manufacturing industry and industrial construction as well as the need for improvement of the methods were also discussed. Also guidelines used in building industry were handled and compared to guidelines used in the design methods. This corresponds to the first part of the aim, repeated below:

- Investigate potential design methods in manufacturing industry and guidelines used in building industry. Identify their need for improvement in order to match connection design in industrial construction.

Further on, a design method for structural connections in industrial construction has been developed. The method consists of four parts: guidelines for industrial construction, a checklist for absolute demands, an assemblability evaluation method, and a procedure for part reduction. The design method was tested with help of a case study including eleven connections. This satisfies the second goal repeated below:

- Develop a design and evaluation method for structural connections in industrial construction, including case study verification.

Suggestions for Further Studies

The developed design method handles the assembly in industrial construction. However, as mentioned in Section 0, other aspects are important during connection design. Therefore further research is needed concerning these aspects. Furthermore, the developed method can also be improved as follows:

Quantitative method: The method developed in this project is, as earlier mentioned, a qualitative method. This means that design proposals are weighted and given a grade. A quantitative evaluation method giving an estimated time and cost for assembly could be preferred. In order to develop such a method, an extensive study has to be performed and a time bank has to be compiled. It would be useful to get an estimation of the cost saving and the pay-off time for a certain redesign.

Narrow methods: Another possibility is to have specified methods for each kind of connection, there could for instance be one version for wall-to-wall connections and one version for beam-to-column connections and so on. In this way, the method would be better suited for each type of connection and give more reliable results. The method would on the other hand be less general.

Interactive structure: The method could be improved using an interactive structure where irrelevant criteria automatically disappear. If there are no loose parts, for instance, the criterion handling properties of loose parts could be removed.

Design steps: Other areas could be added to the design method. The step concerning reduction of parts could, for example, be expanded also to minimising the number of assembly operations.

Evaluation of absolute demands: An evaluation concerning the absolute demands might be needed as it can be difficult to fulfil all absolute demands which might result in a compromise. It might be possible to use a similar structure for the absolute demands as used in the evaluation of assembly.

More connections: In this project eleven connections of varying industrialisation degree have been studied. More structural connections used in industrial construction could be tested in order to further develop the reliability of the evaluation method and improve it.

Limits for the assembly index: There are no specified limits for when a design is good enough or when it is acceptable. This is because the assembly index varies depending on the type of connection. The evaluation method might be possible to improve in such a way that it gives comparable results for different connection types. Another alternative is to make a larger case study in order to determine acceptance limits for different types of connections.

Openness – think again, buddy

In this chapter, a suggestion is given for how to define the different perspectives of openness in different systems. The most interesting conclusion is that ***openness in the value-chain and in individual designs are not compatible goals***. If we want openness in both the value-chain and in individual designs, we need many different systems, catering for different market segments. The aim of this chapter is to invite to a discussion on this subject in general and this conclusion in particular.

Introduction

This is a comment you've probably heard in some form.

”We've tried industrialisation before. If we don't develop open systems, we'll be back in the 1960s. Look at the USB-port and the SIM-card.”

Maybe, but probably not. A generally accepted definition of openness is that an open system is affected by circumstances outside of the limits of the system (Eichert and Kazi, 2007). What constitutes and open or a closed industrial system is a matter of definition, and overall of academic interest. The important issue is what consequences different systems have from different viewpoints; what options the offer for choice and variation (Engström and Johansson, 2007).

In many respects, it is difficult or impossible to draw a clear demarcation line between the construction sector and the manufacturing industry. Today, both the components and building parts (windows, doors, trusses, bathrooms and so on) are manufactured in an industrial manner. The Swedish single family housing industry has a long tradition in designing and building modularised houses in a factory, transporting them to the site and assembling quickly (Claeson and Widfeldt, 2006). For taller buildings, there are a handful of systems; notably Lindbäcks Bygg AB and Myresjöhus B4 system. Similar methods and systems are now being developed and brought forward by the larger contractors and developers; notably NCC Komplett, Skanska Moderna

Hus and Peab's PGS (Törnros 2007). The image of these systems tends to be that they are developed into closed systems.

So is the development of building manufacturing being done behind closed doors? Does the closed character of the systems make it difficult for independent suppliers to introduce themselves in the industrial arena? We claim that it the other way around. The question is how you define *open* industrial building.

In this chapter, a suggestion is given to that effect. The most interesting conclusion is that ***openness in the value-chain and in individual designs are not compatible goals***. If we want openness in both the value-chain and in individual designs, we need many different systems, catering for different market segments. This conclusion is open for discussion, which indeed is the aim of this chapter. It should be verified by a more thorough study.

What is openness?

There are a great number of different definitions of openness, the traditional one being related to whether or not the system communicates across its borders (see Figure 65 below). In order to develop an up-to-date definition of open systems, it is less useful top define openness from the viewpoint of internal organisation, but instead develop a definition that focuses on what values the openness provides to stake-holders. In ManuBuild, a collection was made (Boudjabeur 2005) of features of the ideal open building manufacturing system. Such a system provides:

- Individual designs
    - User-oriented design
    - Close interaction between the architect and user at the first phases of design
    - Increasing flexibility of the house/apartment
    - Dividing the building into fixed support and flexible infill
- Compatibility and interchangeability of components
- Alternative assemblies
    - Use standardisation
    - Standardised connections that are used by most if not all producers of building components
- Future changes
    - Allows for changes at a later date without costly measures

Some of the aspects above are solutions, some are requirements. Some are related to process, some to technology. However, in ManuBuild, there is the growing insight into the mechanisms of openness. In terms of whether a system is open or not, there are four perspectives that need to be dealt with.

1. **Recipient**
   Open for whom? For the user, for the producer, for the architect, …?
2. **Aspect**
   Open from what viewpoint? When it comes to the suppliers in value-chain, customer choice, future changes, …?

3. **Time-frame**
   Open for which time-frame? Open for substitution of suppliers for each project or on longer time-scales?
4. **Level of complexity**
   Open at which level of complexity? Open for client choices of tile colours or apartment layout? Open for interchangeability of brick manufacturer or of the whole load-carrying frame?

Every building system represents a unique combination of these four perspectives. Thus, openness becomes a concept which is less than clear-cut. Each and every system is likely to be able to produce a combination of perspectives so as to be defined as open. But each and every system is just a likely to produce a combination of perspectives so as to be defined as closed. For example, when it comes to the interchangeability of suppliers and products, it is vital that we take into consideration the level of production complexity, see Figure 64. In lower-level production, openness is not difficult to attain; it is easy to substitute the brand of bricks and mortar, cement and reinforcement, for another. At this level of complexity, openness is facilitated by product standards and building codes that guide the whole value-chain as to what the specifics are/should be for a product of a certain type. In higher-level production, substitution of parts is not as simple because lower-level production will have an impact on the choice. Because of all the implications in a building system of the load-carrying frame, it is not easy to substitute a load-carrying frame supplier for another. In addition, at this specific level of complexity, building and production codes no longer aid in the communication of requirements.

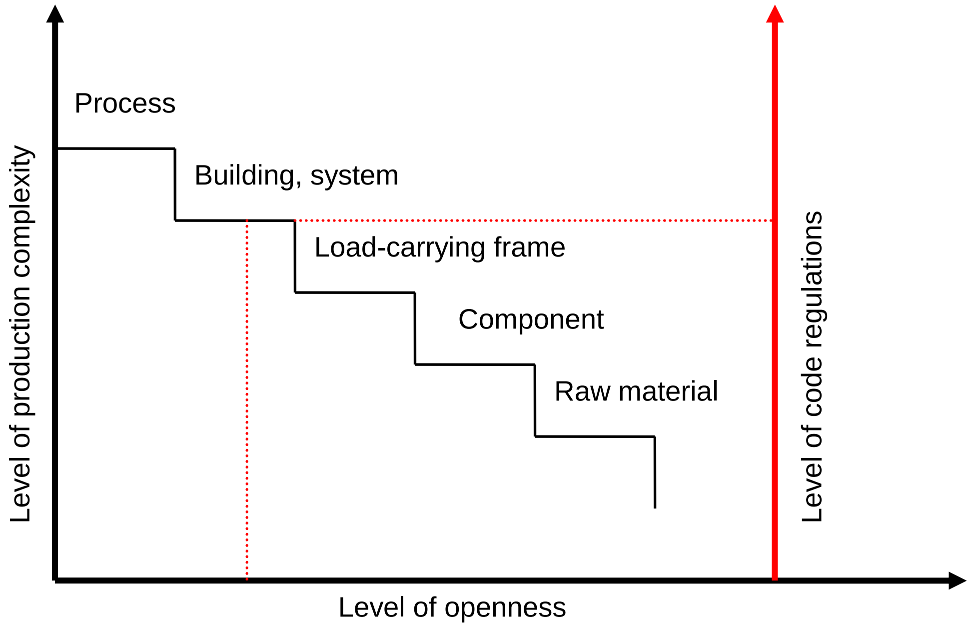


Figure 64: Level of openness vs. level of production complexity

Arguably, openness as a one-dimensional label on building systems can be considered to be a thing of the past. Concepts for openness should focus on the user (user-driven variations and flexibility) and on a common European construction sector (interchangeability in the value-chain and standardisation). In both these cases, openness depends on compatible technology and a common methodology, where methodology is the one least focused on so far in our sector. The reasoning in this paper is that with a common methodology, we can always develop common technology. The opposite is less likely to happen.

Drawbacks with openness

What perspectives of openness should we focus on, and how open do we want our systems? In the ideal open system, there will be a handful of problems to deal with. For example, a system that is open to interchangeability (recipient and aspect) of wall components (level) between each project (time-frame) will have the character of lowest bidder for wall components, and thus exhibit the same problems at traditional construction does today. Because of this, quality and long-term collaboration will suffer. With the constant possibility (threat) of introduction of new suppliers, the owner of the system looses overall control over the system performance, and is likely required to introduce additional quality control procedures. In addition, there is nothing to gain in providing knowledge feed-back to a product or a process that is completely open (i.e. unique). Another important problem is that there is very little business incentive for anyone to maintain and improve a completely open system.

Within the construction sector, there is today already a strong tradition of openness. Even the industrial systems available offer opportunities for choice and variation form different perspectives. Different system developers focus on different perspectives of openness, which provides us with a rich flora of systems with different features. For example, most industrial systems are open to new suppliers because they work with strategic partnerships that vary over time. There is a plethora of different industrial building systems in Sweden alone. A technical compatible European – or even only Swedish – construction sector is not feasible, due to the overwhelming complexity involved. What is more important, it not even desirable. Technical compatibility (for example through standardised and exchangeable components) removes the incentives for companies to develop the systems. The pursuit of the technically open system risks being a business impediment for the introduction of industrial thinking in the sector. Arguably, technical compatibility over many systems is neither possible nor desirable.

Requirements on open systems

Which requirements should we put on an open building manufacturing system?

Many of the ongoing development efforts within building manufacturing emphasises collaboration with key partners in the value chain; that system owners and suppliers develop the methodologies, systems and products together. This brings up a key issue for how an open system can (should) be expected to work – it is easy to be led to believe that a partnering contract with a system owner and a supplier restricts this market niche for the major part of the value chain. In a sector that is characterised by open systems, buyers compete with each other in the open market and are able to sell their products and services to more than one company.

An open building system has a number of specifications and ground rules for the designs but are otherwise open for variations and choices, it is for example open for all suppliers that meet the specifications (Claeson-Jonsson 2006). We argue that the specifications should not be technical in their nature, for example connections and interfaces common for several systems. With a system with technical specifications, the system owner must provide suppliers with designs to offer tenders on. On the other hand, a system that is developed in collaboration builds on openness within the working group. With such systems, all involved have the opportunity to develop together the technical content that we must agree on at the end of the day.

It is time for us to get away from the technically inspired image of openness and instead think about *why* we want open systems. The reason must be in order to have our options open for example for *varying products* (the perspective of the client and society, respectively), an *open market for both suppliers and system owners* (the perspective of the sector and of society, respectively) and *future changes of the building* (the perspective of the user). We believe that the possibilities to reach such goals are more dependent on what *working principles* we have in common than what *products* we have in common.

Openness then means that options and choices are open. Every time openness is used to describe a system, it needs to be specified which perspective is being used. Is the system open from the perspective of future changes or new suppliers? A comprehensive definition of the concept of openness in building manufacturing systems is lacking. A suggestion (Engström and Johansson, 2007) we would like to bring forward is qualitative in its nature:

> A system that is *open* from a certain perspective offers a number of choices and variations relevant to the perspective in question.

From this it follows that a system that is *closed* from a certain perspective offers no or only a very limited number of choices and variations relevant to the perspective in question. Below follows a selection of important perspectives (and the choices related to each perspective), from the viewpoint of the client and a common European construction sector.

- Design
  The system should offer individual, varied designs. For example, client-driven design processes offer choices in the form of flexible houses and apartments.
- Production
  The system should offer possibilities for interchangeability in the value-chain.
- Transparency
  The system should have a predictable and developed

process, for example with a decision schedule, which highlights the choices open to the client.

- Standardisation
  The system should be standardised at the level of article numbers, and with standardised methods of communication and configuration, which opens possibilities for many different products form the same, rational process.
- Future changes
  The system should allow reasonable changes during the life-time of the building without the need for expensive, extensive remodelling work. A system that is open from this perspective typically divides the building into permanent structure and flexible infill, sometimes with infill being subdivided based on the different expected lifetimes.

A technically-economically reasonable requirement for future changes is the opportunity to easily substitute the kitchen and bathroom and to move interior walls. A completely open system from this viewpoint would allow moves of walls separating apartments, an opportunity which probably is not economically feasible. This might be considered a good example when completely open systems are not the sole saviour.

Unsuitable requirements

Which requirements should we not put on an open building manufacturing system?

The demand for quality buildings to reasonable cost is obvious but has very little to do with openness. The demand from society on low living costs, from clients on quality levels and from the sector on lower building costs are relevant to the manufacturing aspects but should not be included in the requirements for openness.

In this paper, we want to highlight a problem and a possible solution in the development of open, industrial systems in the construction sector: the compatibility and exchangeability of components. Systems that do not live up to this requirement are often considered to be closed and lead the thoughts to uniformity of the 1960s. It is important to remember that the methods that we borrowed from the manufacturing industry in the 1960s were mass production methods and standardisation towards the market. Today, the methods we borrow concern mass customisation and internal standardisation. Thanks to these methods, it is possible to discuss a process orientated characterisation of open systems. Today, we do not need to require technical compatibility to be able to create variation.

We do not think it is necessary that direct compatibility and exchangeable of products are included in the requirements on openness in building systems. Such a requirement on product level would mean that is should be possible to build a storey with the Corus Living Solutions system in a building otherwise built with the NCC Komplett system. Few will argue in favour of this being a necessity. It contributes just as much to variation if the compatibility means that Corus and NCC are able to buy subsystems from the same supplier, who also can partner up with Skanska and Carillion.

Development of open systems – what now?

In our ambition to develop openness in common over the sector, we must find a way to turn the business-based obstacles to openness into possibilities. The traditional definition of an open system is that is can communicate with the environment outside of its own system borders. A closed system does not do this, see Figure 65. We have argued above that whether a system can be classified as open or closed depends for example on at which level the border is put in place. In the language of this definition, our two tasks must be the following.

- to facilitate that information can cross borders easily, irrespective of where the borders are laid down, and
- to facilitate that this information id interpreted correctly by the receiver..

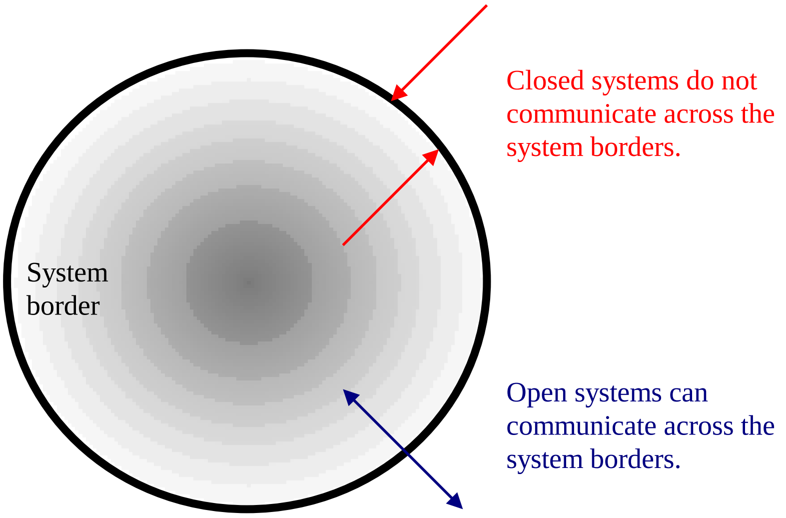


Figure 65: The traditional definition of open and closed systems

The work must aim to develop methodologies that many companies and organisations can use, adaptable for each company's product, situation, business segment and preferences. It is more important that a new supplier and I both are able to work according to the same industrial methodology (for example Lean thinking) than that the supplier manufactures a product that already today fits into my technical system. For example, technically, the sector should together develop standardised methods of communicating interfaces between components and building parts, in order for requirements on function and/or design can be given unambiguously (Lassl and Löfgren 2006). This opens opportunities for collaboration without requiring technical compatibility from the outset, where everyone can pursue their own technology development and when doing business communicate the results with the same language. Direct standardisation, exchangeability and compatibility of interfaces and components become questions to handle *within each system* not between different systems. The automotive industry is very successful at this (Andersson and Suber, 2006).

Such development work should include raising knowledge and awareness in the sector of industrial business strategies for example so-called *product offers*), supplier collaboration, client-driven processes, transport and logistics (particularly just-in-time and minimised stocks), manufacturing and information exchange. The turn from project approach to process approach is the key. This overall industrial maturity creates possibilities to communicate and collaborate, irrespective if our systems are technically compatible or not. Suppliers will be able to sell to different buyers, system-owners will be able to choose between different suppliers, with similar business approach and methodologies. The possibilities for varying designs remain, which is another important aim of openness.

Structuring openness

In order to be able to discuss the consequences, opportunities and limitations of openness, it is useful to structure this complex concept in an accessible format. On the next page can be found a suggestion (Figure 3) for such a structure; a spider-web diagram giving the different perspectives of openness. This diagram can be used as a basis for discussions on one's own system, or for comparisons between different systems.

The diagram gives the four perspectives (with subheadings) of openness and five circles that are used to grade a certain system for the openness of each perspective and each subheading. In the diagram has been put two fictitious building manufacturing systems. The red line represents a volume-element system with the characteristics that Skanska's *BoKlok* or NCC's *Det Ljuva Livet* might exhibit. This system does not offer very much opportunity for choice of individual designs and can be fairly simple in its structure. Consequently, it is open for options in the value-change and on fairly high levels of complexity. The purple line represents a parametric system with the characteristics that Open House or NCC Komplett possibly might exhibit. Such systems are open for individual designs. This means that they must necessarily be complex in their structure, which leaves less room for direct openness in the value-chain.

The grades in the diagram are defined as follows.

- 4p Absolutely open, no restrictions
- 3p In general very open, requires limited work to utilise openness
- 2p Limited options open, potential for more
- 1p Potential for options, requires extensive work
- 0p No realistic opportunity for options

In order to be able to make comparisons objectively, it is necessary that all points (not just the five circles) in the diagram are defined. For example, the purple line in green circle is a 3, which signifies that openness at the level sub-system in general is very open, and requires limited work to utilise the openness. In order to be made accessible and understandable, this generic description needs to be complemented by an example; it might mean that the system is not developed for a certain ventilation system, so that both the ventilation system and load-bearing frame are open.

It would be an interesting exercise to develop such a methodology and make comparisons between a set of systems available, with different characteristics. From this can be drawn conclusions of what openness is available today and what is necessary for a common European construction market. It is clear even from this simple exercise (Figure 66), that if the aim is to open the value-chain for different actors, the level of complexity in the systems should be kept low. However, this would have the direct consequence that there would be less openness for individual designs form each system. If we want openness in both the value-chain and in individual designs, we need many different systems, catering for different market segments. Again, this conclusion is open for debate and should be verified by a more thorough study.

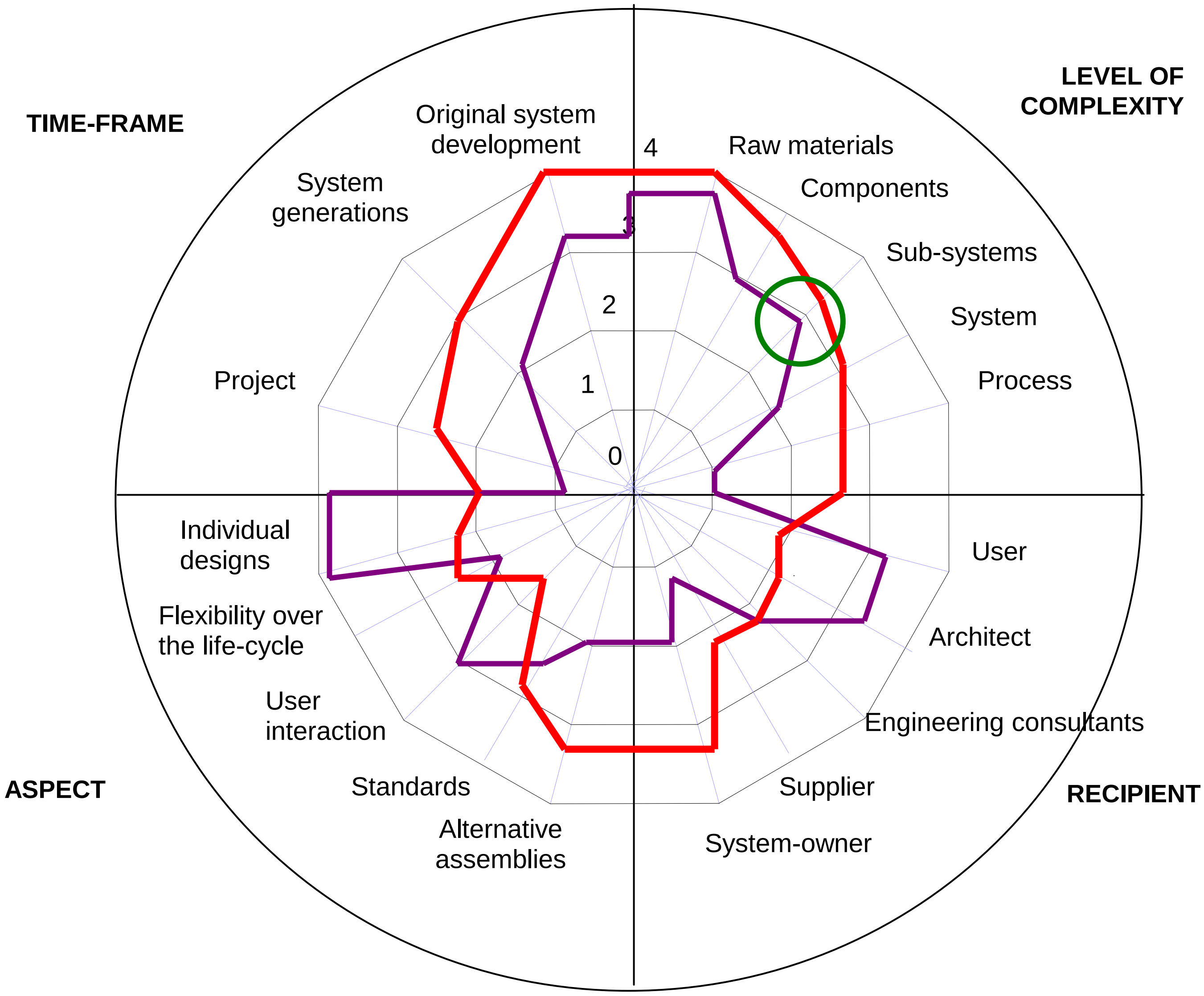


Figure 66: A suggestion for a spider-web diagram for structuring the different perspectives of openness in building manufacturing systems. See explanation above.

Openness – In summary

Any system can be defined as open (or closed) only by a decision to discuss openness for a certain recipient, from a certain viewpoint, a certain time-frame and a certain level of openness. We should talk about openness as the multifaceted concept it inherently is, and we should not seek it in the *products* we produce but in the *principles* that we use. These principles will develop with increasing industrial maturity in the construction sector. They will become important tools for the sector to be able to utilise that we move manufacturing into the factory. With such a definition of openness, the business incentives remain for developing systems, varied design, and for new companies to be introduced into the value-chain and so on. Unilateral categorisations whether or not different systems are open become semantic exercises.

In this chapter, a suggestion is given for how to define the different perspectives of openness in different systems. The most interesting conclusion is that ***openness in the value-chain and in individual designs are not compatible goals***. If we want openness in both the value-chain and in individual designs, we need many different systems, catering for different market segments. The aim of this chapter is to invite to a discussion on this subject in general and this conclusion in particular.

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APPENDIX A

Connection Design Method

Contents

Introduction

This design method addresses connection design in industrial construction. It is developed in the Master's Project *Connection Design for Easy Assembly*. The following document contains the method without any explanations and motivations of its structure. The method aims to help designers to design and evaluate structural connections which are easy to assemble. The method is preferred to be used in an Excel-Document but will here be presented as manual worksheets.
The design method is divided in four steps. Each step is presented in separately chapters but will be shortly described here:

Guidelines

The design method starts with guidelines that are presented in order to provide the designer with background information of connections design in industrial construction. This background information is aimed to help the designer to develop industrial connections that are easy to assemble.

Checklist for Absolute Demands

The next step is absolute demands; if a connection should be evaluated it is important to first make sure that the connection fulfils its absolute demands. These demands have to be fulfilled in order make the connection work properly, e.g. the load bearing capacity has to be fulfilled. The absolute demands are controlled with help of a checklist. If the absolute demands are fulfilled the next step in the method is to evaluate how well the connection is suited for assembly.

Assemblability Evaluation Method

The evaluation handles desirable demands, if these demands are neglected the assembly might be more difficult. The evaluation consists of criteria related to assembly which are divided into statements. The connection is graded depending on the chosen statement of each criterion. The result of the evaluation is an assembly index, which describes the connection's assemblability relatively, and a list of which areas that can be improved. The improvement can either be a change of the connection itself or the whole system. After the changes it is important to control if the absolute demands still are fulfilled. When a connection has satisfying result in the evaluation the final step can be performed.

Reduction of the Number of Parts

The last step in the design method concerns reduction of the number of parts in connections. The main reason for the part reduction is to make the assembly easer as fewer parts will result in an easier assembly. Besides, if a connection consists of fewer parts, it will likely be easier to manufacture.

Guidelines

Appearance	Connection details should not be visible in the final building if they are judged to reduce the esthetical value.
Construction Environment	Production and assembly should be performed in a controlled and dry environment.
Costs	Elements and their connections should be as cost effective as possible both regarding manufacture and assembly.
Crane Time	The crane time needed for each element should be kept to a minimum.
Ergonomics	Production and assembly should be planned in order to improve the workers ergonomics.
Fixation	Connections should be easy to fixate by as few operations and assembly workers as possible.
Fixation Methods	Only clean and dry fixation methods should be used and not connections methods as for instance welding and grouting.
Maintenance	Connections are preferred to be designed for a small need of maintenance. If maintenance is needed it should be easy to perform, e.g. regarding access.
Multipurpose Connections	Connections are preferred to be used for other purposes than load bearing in the service state, e.g. used as lifting points during assembly.
Number of Parts	The number of loose parts used in connections should be kept as low as possible.
Prefabrication Grade	Elements are preferred to be fully prefabricated; no, or only little, supplementary work should be needed.

Stability	Elements should be stable as soon as possible.
Symmetry	Loose connection parts should be made as symmetrical as possible.
Temporary Supports	Temporary supports should be avoided.
Tolerances	Connections' tolerances should be well adapted to their building system and easy to adjust.
Tools	The number of tools needed for assembly should be kept to a minimum. Large and heavy tools should be avoided.

Connection Description

INFORMATION OF THE STUDIED CONNECTION

To use the design method each method studied must be described. Fill in the connection description and add a connection picture below in order to make clear which connection that should be studied.

CONNECTION TITLE

INSERT CONNECTION DESCRIPTION HERE AND A TITLE ABOVE

PICTURE

INSERT CONNECTION PICTURE HERE

Absolute Demands

CHECKLIST

If some of the relevant requirements are not fulfilled, these have to be fulfilled before the connection is possible to use. If all relevant requirements are fulfilled the studied connection can be rated using the evaluation method. Further requirements can be added if needed.

Does the connection studied fulfil the following requirements?

Is the connection…	**Yes**	**No**	**Not relevant**
able to resist applied shear force?			
able to resist applied tension force?			
able to resist applied compression force?			
able to resist applied bending moment?			
able to resist applied twisting moment?			
tight regarding sound?			
tight regarding air flow?			
tight regarding moisture?			
tight regarding water?			
tight regarding heat?			
having tolerances suited to its system?			
able to resist chemical attack?			
able to resist fire?			
able to handle creep?			
able to handle shrinkage?			
stiff enough not to cause too large deflection?			
safe regarding fatigue?			
weather resistant?			
possible to assemble?			
prevented from unintended disassembly?			
invisible when completed?			

Evaluation

INSTRUCTIONS

Start by choosing the importance of each criterion, described below. The importance factors should only be chosen from the numbers below as this gives a balance in results and a possibility to compare results. Then select the statement that match the connection best, mark it with an "x", and add comments and assumptions. The grade of the criterion will automatically be calculated as the importance times the criteria point described below. The points are, as the importance, fixed values and should not be chanced. When everything is filled in, the result will appear on the result page.

IMPORTANCE

The importance of each criterion regarding the connection can be chosen according to the scale below.

0	Not relevant
1	Relevant
2	Extra important

CRITERIA POINTS

All criteria are given a point, shown below, depending on the choice of statement.

3	Desired
1	Acceptable
-1	Unacceptable

RESULT DESCRIPTION

On the result page all grades are compiled. It can be seen which criteria that are satisfactory and which that has to be considered in a redesign. Results from criteria that could be improved are marked red and good results are marked green. Also the number of handled criteria, a mean grade of the connection based only on the handled criteria, and an assembly index are shown.

RESULT

CONNECTION TITLE

NUMBER OF CRITERIA USED	0
MEAN GRADE	-
INDEX	-

SUMMARY OF CRITERIA

Criteria	Importance	Point	Grade
Stability	0	-	-
Positioning of Elements	0	-	-
Positioning of Loose Parts	0	-	-
Number of Loose Parts	0	-	-
Size of Loose Parts	0	-	-
Weight of Loose Parts	0	-	-
Need for Assembly Workers	0	-	-
Safety for Workers	0	-	-
Tools	0	-	-
Accessibility	0	-	-
Fixation Method	0	-	-
Protruding Parts	0	-	-
Multi-Purpose Connections	0	-	-
Fool Proof	0	-	-
Demountability	0	-	-
Tolerance	0	-	-

Stability	IMPORTANCE:	0

Connections that provide stability fast and easy are preferred as the time needed for crane operations will be reduced.

STATEMENTS	CHOICE	GRADE
The connection provide stability at once		-
Stable after a small fixation or adjustment of the connection		
Major fixation operations or temporary supports are needed		

Comments and assumptions:

Positioning of Elements	IMPORTANCE:	0

Elements should preferably be guided into their final position.

STATEMENTS	CHOICE	GRADE
The connection guides elements into position		-
The connection partly guides elements into position, e.g. self guiding in one direction		
The connection provides no self guiding for elements		

Comments and assumptions:

Positioning of Loose Parts	IMPORTANCE: 0	
Loose connection details are preferred to be self guiding.		
STATEMENTS	**CHOICE**	**GRADE**
All loose connection details are self guiding		-
Some loose connection details are self guiding		
No loose connection details are self guiding		
Comments and assumptions:		

Number of Loose Parts	IMPORTANCE: 0	
The loose connection parts needed during assembly should be as few as possible. In this case subassemblies are defined as one part.		
STATEMENTS	**CHOICE**	**GRADE**
One loose part (or no loose parts)		-
Two or three loose parts		
More than three loose parts		
Comments and assumptions:		

Size of Loose Parts	**IMPORTANCE:**	**0**

Long or wide loose parts that are hard to handle should be avoided.

STATEMENTS	CHOICE	GRADE
The longest measurement is between 2 cm and 30 cm		-
Some connection details have measures between 1 cm and 2 cm or between 30 cm and 50 cm		
Some connection details have measures smaller than 1 cm or larger than 50 cm		

Comments and assumptions:

Weight of Loose Parts	**IMPORTANCE:**	**0**

Heavy loose parts should be avoided.

STATEMENTS	CHOICE	GRADE
No parts weigh more than 1 kg		-
Some parts weigh between 1 kg and 3 kg		
Some parts weigh more than 3 kg		

Comments and assumptions:

Need for Assembly Workers	IMPORTANCE:	0
The need for assembly workers should be minimized. Every operation should preferably be performed by only one worker (except crane operator). No special skills, e.g. welding skills, of the workers should be needed.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can be assembled by one worker with no special skills		-
The connection can be assembled by two workers with no special skills		
The connection has to be assembled by more than two workers or by workers with special skills		
Comments and assumptions:		

Safety for Workers	IMPORTANCE:	0
The risk for workers getting injured in the assembly process because of the connection should be minimized.		
STATEMENTS	**CHOICE**	**GRADE**
No risk for workers getting injured		-
The risk for workers getting injured is small		
The assembly work is risky for the workers		
Comments and assumptions:		

Tools

IMPORTANCE: 0

Heavy, large or cumbersome tools should be avoided and the number of tools should be kept low.

STATEMENTS	CHOICE	GRADE
Not more than one small tool needed for the assembly		-
Two or three small tools are needed		
Many different small tools or heavy, large or cumbersome tools are needed		

Comments and assumptions:

Accessibility

IMPORTANCE: 0

Connections should be accessible for the workers at assembly if needed. Avoid to place connections in tight sections or outside at high levels.

STATEMENTS	CHOICE	GRADE
The connection can be handled from one side only with easy access		-
The connection must be handled from two sides, but is easy to access		
Restricted access or more than two sides needed for handling		

Comments and assumptions:

Fixation Method	IMPORTANCE: 0	
Fasteners should be designed as simple as possible. Snap fits are preferred in comparison with screws while complex connections such as welding, grouting and other wet connections should be avoided.		
STATEMENTS	**CHOICE**	**GRADE**
The connection provides fixation easily using snap fits or with help of a simple motion		-
Screws are used as fasteners or a combination of motions is needed		
Complex connections such as welding, grouting or other wet connections are used		
Comments and assumptions:		

Protruding Parts	IMPORTANCE: 0	
It is important that connections are not fragile or harmful to components, protruding parts, other connections and personnel.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is not harmful to elements or fragile in itself		-
Damage is possible but can be repaired easily		
Damage is possible which is difficult to repair or result in that whole elements have to be replaced		
Comments and assumptions:		

Multi-Purpose Connections	IMPORTANCE: 0	
Try to integrate lifting devices in the connection. The elements should hang straight when lifted.		
STATEMENTS	**CHOICE**	**GRADE**
The connection can serve as lifting device without changes		-
The connection can serve as lifting device with of some extra equipment		
The connection does not serve as lifting device		
Comments and assumptions:		

Fool Proof	IMPORTANCE: 0	
It should preferable be impossible to perform a misassembly. For example parts should only be possible to assemble in a certain position and screws should not be possible to fasten too hard or too loose.		
STATEMENTS	**CHOICE**	**GRADE**
The connection is hard to misassemble		-
The connection can be misassembled but guiding features are provided in order to prevent misassembly		
The connection can easily be misassembled		
Comments and assumptions:		

Demountability	**IMPORTANCE:**	**0**
Elements should be possible to demount without getting damaged.		

STATEMENTS	CHOICE	GRADE
Disassembly is possible without causing damage to elements or the connection itself		-
Disassembly is possible without causing damage to elements, but the connection itself can be damaged		
The connection provides no disassemblabillity		
Comments and assumptions:		

Tolerance	**IMPORTANCE:**	**0**
Connections that are easy to adjust regarding tolerances are preferred.		

STATEMENTS	CHOICE	GRADE
The connection adjusts automatically when assembled		-
The connection is easy to adjust for size variations		
The connection is hard to adjust or require extra assembly time when adjusted		
Comments and assumptions:		

Part Reduction

MINIMIZE THE NUMBER OF PARTS USING THE FOLLOWING QUESTIONS		
Answer the following questions for each part in the connection. If all questions concerning a part result in negative answers, the studied part could be eliminated or combined with another part.		
Question	**Yes**	**No**
Does the part move relative all other parts?		
Must the part be of another material than other parts?		
Must the part be separated from other parts, or else one or more of the other parts' assembly will be impossible?		