DESIGN OF A SET OF STOOL AND TABLE WITH A SUSTAINABLE APPROACH BY USING DFA AND DFE PRINCIPLES.

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Alejandro Guil López
Isabel María Guerrero Valadez

Supervisor: Nathanael Kuipers
Examiner: Peter Thorvald
Assurance of own work

This project report has on 08/03/2017 been submitted by Alejandro Guíl López and Isabel María Guerrero Valadez to University of Skövde as a part in obtaining credits on basic level G2E within Product Design Engineering.

I/we hereby confirm that for all the material included in this report which is not our own, I/we have reported a source and that we have not – for obtaining credits – included any material that we have earlier obtained credits within our academic studies.

Alejandro Guíl López

Isabel María Guerrero Valadez
Abstract

This report covers the conduction of a final thesis project for the University of Skövde in collaboration with Carlos Jimenez Design studio (Spain).

The aim of this project was to design and present a set of furniture consisting in a high stool and a high chair of a similar nature to the ones which are usually found in bars, oriented to the domestic environment and to the Scandinavian market.

The main special characteristic of this project is that the design has been carried out with a focus on environmental sustainability, which has been approached in such a way that assembly has a big part in it, which at the same time relates to user experience. Therefore, the project combines design for assembly (DFA), design for environment (DFE) and user experience design (UXD) in such a way that all the approaches taken for each of these factors are interrelated in complete and thorough design process, were all the aspects of the final product have been taken into account.
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1 INTRODUCTION

This report presents the development of a set of high stool and high table intended for a domestic dining room, designed through a sustainable way. This proposal is carried out in collaboration with Carlos Jiménez Studio, who agreed to collaborate in this project.

Nowadays, there is an increasing demand for furniture that takes values of sustainability in a thorough and serious way due to a more educated consumer culture and trend (Clark et al., 2009). More and more companies are getting aware about sustainability importance saving material, rethinking product properties or designing eco-friendly products.

An approach to this sustainable objective that is gaining popularity is the adoption of an alternative assembly. Many furniture companies attempt to create an assembly process that is carried out entirely by the user, trying to make the process as easy as possible. Examples of this are present all across the Scandinavian market, such as the new Lisabo table by Ikea (see Tendencies section).

This project aims to create a set of furniture that follows this trend, however the approach is much more thorough as both the table and the stool will be designed to be self-assembled avoiding extra fasteners (screws or chemical adhesives). This makes the set more sustainable and at the same time guarantees a simple and intuitive way to build both furniture pieces.

Therefore, this project aims to create a product in which assembly, environmental sustainability and user experience are profoundly interrelated and worked towards in such a way that the best result possible is guaranteed for all of them.

1.1 PARTNER COMPANY

Carlos Jiménez Design is a design studio in Almeria, Spain, whose most prominent feature is its style, a mix of Scandinavian and Mediterranean style. Its main activity is based on development concept, designing home furniture and lighting (See figure 1 and 2) among other activities, such as branding and toy design.

Figure 1: Piece of KAAJA collection.  Figure 2: ORIGEN lamp.
The studio is seeking to launch a set of furniture with the characteristics that have been stated before, in the Västra Götaland region, to be manufactured at Tibro and sold in this city and neighboring ones.

1.2 MISSION

The goal of the project is to develop a set of stool and table within a sustainable approach following DFA (Design for Assembly) and DFE (Design for Environment) principles. DFA aspects will be applied in order to reduce the joining pieces and avoid the use of contaminant chemical adhesive and ensure the correct assemble and function of the product guaranteeing an easy and fast assembly by the user. On the other hand, DFE will be helpful for the material choice and the way to manufacture them.

Furthermore, some issues such as packaging will be taken into account in order to make sure a good packaging condition with minimum space required, which will be tested by checking the measures are under a certain threshold, such as dimensions of pallets. The main purpose of this matter is to save material to pack, enable it to be recycled and reduce the use of transports to carry the product.

These statements will be assessed throughout a Life Cycle Assessment to get a good result regarding sustainability, meaning a reduction of the Carbon footprint and polluting rates during production, as well as a cradle to cradle design, meaning that the whole product is either recyclable or reusable.

By last, the product features aim to have a satisfactory user experience provided by the self-assembly properties, as it is said previously and a good ergonomic characteristics.

1.3 METHOD

Every design problem needs to be tackled according to a certain methodology that has been previously stated. This methodological approach will prevent the process from skipping steps and outputting an unsuitable answer to the problem the product development project aims to solve.

A common approach to modern design problems are descriptive models of design methodology, which, as described by Cross (2008) are heuristic processes, which aim to generate ideas early in the projected, subjecting them to analysis and evaluation in order to determine their suitability. Inside these methods, it has been chosen to follow a model (See figure 3) created by French (1985). This model was chosen because it is a simple methodology that has been known for working well with projects that are desired to come up with a physical product, as this project does.
NEED
Statement of the necessities that the product needs to assess. Basically it consists in a brief, stated in the previous section, where the functions the product is going to cover are explained shortly and clearly. This will be done at the beginning of the project, taking into account the company’s necessities.

ANALYSIS OF THE PROBLEM
An important part of every project, this phase is aimed to gain a better understanding of the problem parting from the brief, which merely an initial statement of necessities to cover. In this project this will be achieved by three courses of action mainly:

- Research: literature analysis based on consulting different sources of diverse subjects all of them related with the problem which the project is aimed to solve. The literature research is directed to gain a better understanding of the problem and the context in which it is situated.

- Market trend analysis: conducted via looking at possible competitors and assisting to design fairs. This phase is considered crucial for understanding how this problem is viewed in the real market situation and different ways to tackle it.

- Customer survey: an initial customer survey based on multiple choice and open answer questions. This survey was designed with a focus on determining customer preferences regarding several points stated in the brief, with hopes to specify them. An irreplaceable part if we consider the importance User Experience Design gets in this project.
STATEMENT OF THE PROBLEM
After the Analysis of the Problem has been carried out, enough information is assumed to be available for a proper statement of a problem to be made. This statement is supposed to present in a clear and specific way limitations upon the solution as well as the criterion of excellence that it is needed to be worked towards.

This statement of the problem is going to be determined in two different steps:

1. Objectives tree: in this first phase of the statement of the problem the brief is developed into different sub-problems, seeking to identify all of the requirements that the product aims to fulfill. It is done according to the literature research and assuming that some knowledge of the subject has been acquired. In this phase the problems are still presented somehow in an open/abstract form, as the priority here is to clarify design objectives and sub-objectives, and the relationships between them (Cross.).

2. Performance specification: In this second phase of the statement of the problem, the sub-problems stated in the objects tree are specified and quantified, giving them values that act as objectives, and classifying them as demands or wishes. The objective here is to have a comprehensive list of features that the product has to fulfill. This list will be done according to data gathered in the exploration phase.

After this phase is carried out, the design problem that has been proposed is no longer ill-defined and there are some specific requirements that can be worked towards to in the conceptual design phase.

CONCEPTUAL DESIGN
Taking as base the performance specification, in this phase a great number of solutions and approaches to the problem will be presented, all of them having in common that they fulfill as best as possible this performance specification. For better results, this phase will combine both analytic and creative methods:

- Morphological chart: in this method, the different requirements that have been previously stated and that the product needs to fulfill will be arranged in a list. In this list, the different shapes or forms that the different parts of the product might take for each this purpose will be included. This way, a list of all the features and the characteristics that grant the product the ability to include them will be provided. This will be useful from broadening the search for solutions for the project, as different characteristics can be chosen from the list for each of the features, leading to new solutions that otherwise might not be thought of.

- Brainstorming: in the brainstorming session the designers will conduct a communicative exchange of ideas, supporting themselves in the morphological chart. The communication must be fluid and face to face,
understanding proposed ideas and seeking to change or improve them rather than discarding them at first instance.

SELECTED SCHEMES
In this part all the different concepts are analyzed and a decision is expected to be reached. The selection process of the most suitable option needs to be reasonable and according to the requirements of the project.
The selection process will be carried out by firstly evaluating against demand specifications, using a critical success factor chart. This method was chosen because it allows for a rapid evaluation of multiple concepts against vital success factors.
Secondly, after the remaining concepts are guaranteed to fulfill the specifications, a weighted objectives evaluation will be carried out for evaluating the concepts in a more thorough way. This method was chosen due to the capability of weighted objectives to detect the best suitability of different concepts according to specific characteristics. This evaluation will comprehend different sub evaluations for each of the factors, such as LCA, force analysis, stability tests, user tests for assembly, etc.

EMBODIMENT OF SCHEMES
According to French (1985), this phase is aimed towards detailing the present alternatives and, in case there is more than one, choosing a final concept.
The first phase of this part will focus on CAD modelling, creating 3D models of each of the alternatives in a more or less rough way, using the CAD software SolidWorks, and Luxion Keyshot in case renders are needed.
Once CAD modelling is completed, a final choice needs to be made regarding suitability of the concepts. This will be done using an evaluation method directed to UXD: Prototyping. This phase is a primordial one in modern design, since it is almost compulsory nowadays to present a prototype that potential users can interact with, making it possible to conduct tests that will provide insight into user experience matters. The prototype evaluation in this project will be done in two different ways:
- Real size mock-up of the final product in order to test ergonomics.
- Prototypes of different assembly methods printed in 3D in order to test how intuitive and easy is the assembly.
The user tests are expected to be conducted with at least 10 subjects depending on the time left to do them, and they will be as normalized as possible, with a selected methodology beforehand and the same instructions given to all the subjects.

DETAILING
In this final phase where the final alternatives are chosen for both products the main objective will be to detail the product as much as possible, taking into account all the possible aspects such as production, breakage of parts and packaging. This may cause the necessity of going back to the conceptual phase and make changes to the original model.
The final object will be presented with detailed 3D models and renders and a reasonably detailed prototype.
2 ANALYSIS OF THE PROBLEM

In this phase of the methodology the main focus was analyzing the problem in such a way that a final requirement list was obtained. This requirement list establishes a series of specific criteria in a reasonable and justified way. In order to achieve this, the analysis includes both a research of theoretical background as well as empirical studies.

2.1 THEORETICAL BACKGROUND

Here all the relevant information found in different sources is synthetized and covered, with special attentions to the approaches that will be used during the project, mainly focusing in assembly, environmental impact, and user experience, which are the three main aspects of the project that are interrelated between each other.

2.1.1 DFA

Design for assembly (DFA) is the name given to the branch of design which centers on making the task of assembly of the different parts of the product as simple as possible. It is important to take DFA into account in design and production due to its potential to cut costs and time and avoid possible errors during assembly (Fiksel, 1999).

2.1.1.1 Guidelines for DFA

Over the years Design for Assembly has become more and more important in the production approach in companies. It is not surprising therefore that several guidelines have been gathered in order to guarantee a good DFA (Otto and Wood, 2001). In this section these guidelines are analyzed and considered for the following generation phase. The concepts will be valued in accordance to the number of these qualities that are fulfilled (Otto and Wood, 2001).

- Assembly system guidelines:
  - Minimize number of parts by incorporating different functions into a same part. A piece that is multifunctional can save a great number of parts and therefore simplify assembly.
  - Include different parts inside a sub-assembly. Sub-assemblies can help simplify the assembly process.
  - Avoid assembly processes taking place in enclosed environment, where manipulation and insertion of the assembly parts might be difficult due to obstruction.
  - Include indications for insertion in clear way.
  - Standardize parts instead of having a great number of different ones. Can also help to reduce costs.

- Manipulation guidelines:
  - Maximize part symmetry to make reorientation unnecessary and avoid mistakes by the user.
On the other hand, increasing asymmetry can be helpful for orienting certain pieces and difference them from one another.

- Avoid parts that can tangle, or change their features so they are not so prone to tangling.
- Avoid nesting. Nesting occurs when parts stacked clamp to each other. Changes in the design can help avoid this feature.
- Make features that help orienting pieces that are non-symmetric. This can be done often by increasing asymmetry.

**Insertion guidelines:**
- Design mating features to facilitate insertion. Usually done by adding chamfers.
- Provide alignment features for easy insertion. A good approach is the 3-2-1 alignment process, consisting in at least three guides that limit the movement of insertion, two shapes that fit together and one fixation movement.
- Design parts so they are assembled from above without fighting gravity. It is also important to make the part to which the second one is going to be assembled large and relatively heavy to provide a good and steady base for the assembly to take place.
- Preferably make the direction of assembly of all the parts the same so the parts do not need to be tilted or turned around.

**Joining guidelines:**
- Reduce the number of fasteners by using certain types of alternative holding methods, such as tongue in slot joint.
- Define the location of the fasteners in an accessible place, avoiding enclosures or narrow locations.
- Avoid fastening in angled surfaces, working towards flat fastening.
- Make sure a proper space is left between each fastener.

### 2.1.1.2 Types of assembly

Before going into the design phase, it is necessary to understand that the fixings and joints are a decisive part of the project and will affect assembly, environmental, and user experience factors. Knowing this, it is important to consider all the different characteristics of each kind of fixing and assembling element in order to guarantee that the requirements of the product are fulfilled. In this section a research of the existing assembly elements which are most used in the furniture market has been conducted.

**MOST POPULAR SELF-ASSEMBLY ELEMENTS**

The growth of the market in Ready To Assemble (RTA) or flat-pack furniture has led to an increase in the number of unions used in them. Here are listed the most common unions in self-assembled pieces of furniture (Lawson, 2013).

These parts, usually made out of different types of metal or plastic, often require tools to be assembled correctly, but they are inexpensive and they make it possible for users to assemble them, even though they can be difficult at times. The most used are cam and bolt systems, which enable panels to be fixed together requiring
a screwdriver, and corner plates, which often fixate legs in flat pack furniture. As previously stated, these traditional joining methods generally present two faults: the lack in sustainability because of mass produced metal or plastic, and a cumbersome and difficult assembly which needs the usage of tools.

TRADITIONAL WOOD JOINT FIXING METHODS
Another option for assembly in furniture consisting mainly of wood is the adoption of wood joints. These joining techniques were born in architecture in different cultures, both in the west an in the east, with major usage in Japan but also popular in Europe, where innovation was provided too (Zwerger, 2012). These wood joining techniques are especially attractive for this project due to the objective that was set previously of getting rid of adhesives and metal/plastic connectors, and making the assembly as simple as possible. A correctly chosen and applied wood joint could be useful for both these ends, contributing to DFE and DFA at the same time. However, it is mandatory to guarantee that the user can assemble the piece without major complications.

Because of this, different wood joints have been researched generally, firstly just taking into account their geometry and general characteristics.

- Kake joints: Japanese joints usually used in constructions such as pagodas, which connect two pieces of wood in direction in which they run.
  - Simple kake joint: the minor member in the joint is supported in the major member by means of a dovetail. (See figure 4)
  - Kabuto-ari-kake: helmet-shaped end lap joint with through single dovetail (See figure 5).

- Secret dovetail corner joint: used in Europe by cabinet makers, but also found in many Japanese temples and shrines (See figure 6).
- Naijin-keta-yuki-gagyou-tsugite: very simple kama-tsugi joint. Used to interconnect round pieces of wood (See figure 7).

![Figure 7: Naijin-keta-yuki-gagyou-tsugite joint.](image)

- Inago-zashi: very light joint but relatively weak to its counterparts. Usually used for supporting suspended ceilings (See figure 8).

![Figure 8: Inago-zashi joint.](image)

MODERN WOODEN JOINT TECHNIQUES
In the later years furniture design and manufacture has seen an enormous increase in the number of models aiming for alternative assembly methods. Screws and bolts are now considered awkward and obsolete, and adhesives are polluting and do not allow proper disassembly (Lawson, 2013). Furthermore, an assembly method which is somehow innovative or ingenious will obtain the customer’s attention easily because of its attractiveness and unique characteristics.

These ‘new’ wooden joint techniques are in fact based on previous joining techniques which were used a long time ago, and usually just introduce variations to existing techniques to adapt them to furniture design. However, some of them are quite interesting and are worth to investigate further. With the purpose of analyzing these new joint techniques and gain insight into possible joining methods (See figure 9), the Stockholm Design Week was visited and some photos were taken there.
These wooden joints (See figures 9-11) are inspired in traditional techniques that were explained beforehand (See figures 4-8), but they have been adapted for furniture needs, and usually they use a two-movement system that makes them fixate with other elements. They are much more sustainable and attractive than extensively used joints but they have the challenge of being intuitive and easy to assemble by users.

2.1.2 DFE

According to the sustainability definition, as follows: “Sustainability is an economic, social and environmental concept that involves meeting the needs of the present without compromising the ability of future generations to meet their own needs” (Fiell and Fiell, 2013, p.4). Industrial designers conduct a relevant role as a steward with society in order to aware and bring up people about sustainable issues and its importance through the products and services which they design. Hence, this sort of roles is challenging and it takes quite much responsibility.
For that, the way of thinking of industrial designers is essential to achieve these goals, mentioned previously. This sustainable thinking manner can be illustrated by “The Waste Hierarchy” (See figure 12), where the purpose is getting benefits from products, using the least resources and producing as little waste as possible. This hierarchy shows the main alternatives ordered from the most favored (top) to the least favored (bottom).

![Waste Hierarchy Graphic](image)

**Figure 12: The Waste Hierarchy (Fiell and Fiell, 2013).**

As an interpretation of this hierarchy and the concept which it wants to convey, some options have been gotten out from this chart chosen from this chart in order to achieve a sustainable design. These are as follows:

- **Reduce**, using less resources or material, mainly to minimize the energy consumption.
- **Reuse**, give new or same usages or just add to the product a new value.
- **Recycle**, reprocess a material which comes from wastes in order to make them again useful for same or different purposes.

Furthermore, this hierarchy can be broadened showing some new options, all of them applicable into a sustainable design process, such as:

- **Restore**, fix a product to make useful again with the same properties and applications
- **Rethink**, how a designer has to think in order to apply sustainable aspects to a product.
- **Redesign**, this concept is similar to restore but this looks for enhancing the product properties and uses.

So, the waste hierarchy is a set of guidelines very helpful in order to tackle problem within a sustainable approach.

### 2.1.2.1 Approaches

Sustainability is therefore a very broad subject with a great number of different approaches to it within industry and engineering, and more specifically within product development.

The majority of these approaches are based on a framework called Natural Capitalism, which was put together by Hawken, Lovins and Lovins (1999). This framework can be considered the foundation of modern day DFE, and is directed
mainly to change the business model rather than providing design thinking techniques. It dictates that the relation between company and customer is badly approached and it needs to change so the interests of these two are parallel instead of colliding, which is how it happens in today's business model according to the authors. Despite referring mainly to economical and commerce factors, this theory does introduce some interesting factors affecting design and production:

- Radical resource productivity: basically, this aims to use strategies that guarantee that raw materials extracted from the environment are used efficiently, thus increasing productivity, decreasing ecosystem degradation and creating job positions.
- Biomimicry: it is recognized as a way in which waste output can be eliminated from the product by observing and imitating natural processes. This is done by designing processes and products which can be reused and contain no toxicity.

However, the main DFE design thinking current nowadays is Cradle-to-cradle (McDonough and Braungart, 2002). It can be considered as a radicalization of biomimicry in which industry must not only aim to environmental efficient products and processes but to a completely harmless and waste-free product life cycle. In cradle to cradle thinking there can only be two types of materials used in the design process: biological, which will return to the nature to be composted, and technical, which will return to the production cycle to be recycled. Therefore, this materials are rather called nutrients, given the fact that they feed other process when the useful life of the product is ended.

As a part of this design thinking, there exists a certification that has been created by the authors of these theory and recognizes a product that follows the guidelines of Cradle-to-cradle successfully. This certification centers on assessing certain aspects of the product:

- Material health: in this aspect, each material is followed through the design and production, analyzing every chemical present in the processes. Then each of these substances are classified according to their toxicity for humans and environment.
- Material reutilization: this aims to avoid recyclable material, aiming instead for pieces that can be completely disassembled and reused, getting rid of waste altogether.
- Renewable energies: manufacturers are encouraged to commit to the use of renewable energies only.
- Water stewardship: centering on guaranteeing that the output of water is as clean as the input in every process.
- Social responsibility: aiming to design and production policies that guarantee health, safety and rights of the population.

For the assessment of the environmental suitability, the most used framework nowadays is the Life Cycle Analysis (LCA). The Life Cycle Analysis analyses all the different material inputs and outputs of a production process, evaluating their potential environmental impact and interpreting these results. Through the analysis of sources, LCA processes allow to quantify the use of raw materials and energy, and the output of waste in any of its forms in each production stage (Kramer, 2012). Life Cycle Analysis is therefore a central part in every DFE practice.
2.1.2.2 Specific Guidelines

Apart from this general approaches, some specific guidelines oriented to guaranteeing that DFE is followed during product development. Many of these guidelines are suggestive, which means that they come from previous knowledge that leads to think that the outcome if they are followed will be more sustainable for the environment. They reason for this is that DFE standards, apart from those applied by public organisms, are still scarce due to the embryonic state in which DFE is (See figure 13).

![Chart showing the main DFE guidelines and their relation among them (Fiksel, 1999).](image)

As an initial exploration of the design guidelines that could prove useful in this project, a few of these guidelines have been considered to be especially attractive for increasing the environmental sustainability of the products:

- **Material recovery**: mainly by keeping materials as close as possible to the raw material state, specially avoiding composite materials, which suppose an increasing danger to nature. Also, for recyclable materials, an assessment of recyclability needs to be carried out, taking into account the economic attractiveness of recycling it, the quality of the recycled material, and the development of the recycling technology as well as its energy costs and pollution.

- **Component recovery**: designing components that can be refurbished easily, favoring a non-destructive removal of the component.

- **Design for disassembly**: an important requisite for other end of life considerations. Basically done by simplifying component interfaces, i.e. avoiding threaded elements such as screws and adhesives and welds which complicate the disassembly process, and opting instead for snap fits and other assembly methods.

- **Design for waste minimization**: by reducing the quantity of raw material usage, facilitating separability as noted under design for disassembly, and avoiding material contaminants.
Material conservation: by opting for either recycled or renewable materials, increasing the products useful life, designing for packaging recovery and closed-loop recycling.

2.1.3 UXD

User experience design (UXD) refers to all the aspects in which the product can affect a certain user, taking into account all the possible human factors in a design process.

In every design project, UXD is important because of the need the product has to interact with users in a successful way. In this project it is especially significant due to the variety of ways this specific product interacts with the user, during assembly and usage, visually and emotionally.

2.1.3.1 Ergonomics

Ergonomics suppose a central part in every product which is intended to be directly interacted with by humans, and it relates in a direct way with user experience and adaptability.

At first it focused solely in the objective of increasing the performance of the individual in the work environment, following a productiveness-directed approach, which has been changing over time to an approach which rather comprises all the interactions of human beings with both work and leisure environment. Nowadays, ergonomics considers not only system performance but also health and safety, and of course comfortability and human limitations (Berman, 2014).

Therefore, ergonomics are taken into account in every product design process in new product design methodology, and every designer has to take this into account in order to be able to make the resulting product success in an increasingly competitive market where user experience is decisive.

Fortunately, the number of studies in this matter is quite high and covers mostly every kind of product. Given the special importance that ergonomics acquire in seats and surfaces such as tables, a broad variety of studies and research works exist in this matter. From all of them it can be concluded that there are some measures which need to be taken into account when analyzing ergonomics in this kind of products (Oborne, 1995):

- Seat height: the principal body part affected by consists in the soft tissues present on the back of the thigh. Therefore, for normal seats the height adopted is usually not higher than the length of the lower leg. It is also needed to take into account that every user no matter which percentile is able to rest the feet on the floor or in other surface in the case of high stools, however also avoiding a seat that is too low, as it can lead to uncomfortability over time. Market standards situate the ideal height somewhere in between the interval of 590–740 mm (Lawson, 2013).

- Seat depth: this measure should be oriented to guarantee that ischial tuberosities is supported. Therefore, a good insight of the limits of this
distance can be obtained by looking at percentiles for the distance between the back of the calf and the back in the sacral region, which should be slightly bigger than the seat depth. Market standards situate the ideal depth inside the interval of 200–400 mm (Lawson, 2013).

- Seat width: somehow not as important as the previous two but still affecting comfort, the minimum width should be able to support ischial tuberosities while still allowing some freedom of movements. Market standards situate this measure between 450 and 550 mm of width.

- Shape and slope of the seat: seat characteristics are somehow an uncertain field, as there are different tendencies in this matter but none of them are defined as best or worse. However, it can be understood that some shapes such as certain seats with perineal elevation has been rejected by many experts due to the failure of providing a flat and horizontal surface for resting tuberosities. Also it is to be considered that, the softer a seat is, the more the pressure will be distributed.

- Dimensions of the top part of the table: this dimension will affect mainly the ergonomics of the furniture due to its relation with horizontal leg clearance. A top part that is not sufficiently wide will make it impossible for the user to come closer to the table due to the knees colliding either with parts of the table or with other users of the table. It is necessary to take into account that the minimum horizontal clearance established in ISO 26800 is 400 mm (Dul and Weerdmester, 2003).

- Table height: usually, table height ergonomics are analyzed from a work environment point of view. Despite the fact that the product of this project is not intended for this kind of activity, it is necessary to take into account some basic directions that these studies can provide. According to research, the height at which the table top should be situated is related directly with elbow position, however, it is necessary to guarantee that a correct leg clearance in the vertical direction is achieved. An useful approach to this is to create a range of heights that the table can adopt in order to adjust to individual difference in body dimensions. If we consider that according to the ISO 26800 standard the minimum leg clearance is 300 mm, the table height with oscillate between the values of 890 and 1040 mm.

Furthermore, as a suggestion, it has been noted that a growing tendency in the market is to create seats that allow the user to vary the posture by promoting “active sitting” (See figure 14). While this is a tendency that is more directed towards situations in which the user has to be sitting for long time, it is also advisable to take this into account in this project to create a product that allows for a better freedom of movements.
This could be applied to the set this project aims to by making adjustments to the design of both the table and the stool. Another suitable solution for this product would be to adopt the form of pedestal stools. These are stools in which the seat can be tilted forward 15-30°, letting the user adopt a semi-standing posture which relieves the stress on the legs (Dul and Weerdmester, 2003). This pedestal cannot be used for a long time but it could improve comfortability by allowing a better range of movement, which could be considered for this project.

However, ergonomics is not just about the physical properties of the object, as cognitive ergonomics are a necessary part, especially in this project, and they are going to be evaluated via user tests regarding the capability of different groups of people to recognize pieces that belong together during assembly. This is a subject that requires further analysis during this project due to the lack of comprehensive studies in this matter.

### 2.1.3.2 USER-PRODUCT INTERACTION

A successful interaction between user and product is an essential issue to guarantee the proper use of a product. The outcome of this relationship is an experience which can be defined as all possible affective responses that come up with this interaction between human-product (Desmet and Hekkert, 2007). These affective responses are also called product experiences which their kinds depend on a bunch of different aspects such as, the characteristics of the user (context, background, knowledge, prior experience...) or the product features (shape, colour, ergonomics, size... ). Hence, User experience is broken down in these three concepts (Desmet and Hekkert, 2007), as follows: Aesthetic experience, when the product stimulates sensory modalities and trigger sensations throughout touching, seeing or hearing.

- **Experience of meaning**, when the cognitive processes react and analyze the product either by prior experiences, recognitions, analogies or associations.
- **Emotional experience**, is the result of the two previous ones. This outcome is a feeling or emotion as the concept says, towards the product. For instance, frustration, happiness, satisfaction, anger and so on.
Thus, these three terms arrange the following hierarchy (See figure 15):

![Diagram showing hierarchy of user experience, aesthetic experience, and product experience]

Figure 15: Chart about product experience.

Therefore, subjective user experience is a decisive aspect in the success of a product. In this project, the design should focus on creating the best emotional, aesthetic and meaning experience possible for the user, by aiming for unseasonal aesthetics and a design that appears reliable and attractive to the user, relating at the same time with sustainable values. Assembly will also play a very important role here by guaranteeing that the process is intuitive and easy for the user, getting rid of possible failures and insecurities that can lead to a bad subjective experience.

2.1.4 Strength analysis

Even though the design of the pieces of furniture which this project aims to have a specific DFA and DFE approach, it is not to be forgotten that the pieces of furniture have to provide a good service in the primary task they have been designed for.

The furniture designed in this project needs to be able to support certain strains derivated from usage, principally originated due to human support. It is necessary to make sure that the products are capable of withstanding these strains in order to come up with a successful product. If the final products are not capable of doing so, they will be considered faulty and the design may be retouched.

2.1.4.1 Punctual forces

It is a necessity to ensure that the pieces of furniture will not break under sudden forces of higher magnitude. This will assess that the furniture is capable of supporting a much higher stress than the one it is designed for (Eckelman, Hill & Cassens, 1988).

This can be assessed theoretically by using the so-called factor of safety, which assesses the strength of a material or section against a determined force or strain. According to industry standards, commercial-grade furniture need to be able to support at least (Industry standards for commercial-grade furniture, 2009):
- For seating surfaces: 115 kg applied in the center of mass of the top part of the stool, and 80 kg applied in the most dangerous section of the product, plus weight of each part.
- For tables: 80 kg in the center of mass of the top part of the table, and 60 kg in the most dangerous section, plus weight of each part.

For guaranteeing that these requisites are met, a factor of security of 2 for the top part and 1.5 for the most dangerous section will be considered, and the products will be evaluated according to these factors. Ideally, the factor of security will be above 3. These values have been selected due to the fact that they guarantee that the product will withstand forces even bigger than the ones it is expected to. In engineer works, a satisfactory factor of security is usually between 1.5 and 2 (Singh, 2014).

### 2.1.4.2 Fatigue

During the course of its useful life, furniture is subjected to repeated load applications day after day. It is understandable then that very rarely furniture fails over the immediate period of time after it is bought but after a few years of continued usage. Strength decreases with time, therefore it is necessary to take into account fatigue in every performance assessment of furniture (Eckelman, Hill & Cassens, 1988).

The importance of this is especially present in this project since it is vital for the products to fulfill sustainability standards. Therefore, it is of great importance to make sure that the useful life of the product is long with minimum deterioration. According to industry standards commercial-grade furniture need to fulfill certain goals when it comes to fatigue:
- For seating surfaces: needed to withstand a force of 60 kg during 100,000 cycles applied in the center of mass.
- Tables: 30 kg during 100,000 cycles applied in the center of mass.

### 2.1.5 Market Analysis

A research conducted inside the market environment is necessary in every product development project. This research has been conducted in different ways, taking into account the nature of the assembly process, the style that the product is to follow, and the location of the market where it is going to be launched.

#### 2.1.5.1 RTA Market

Assembly in furniture products can be approached in different ways during design. While a fully assembled piece of furniture can be the most comfortable choice for a customer, the production and transport costs are higher, as well as the environmental footprint. This is why Ready-to-assemble (RTA) furniture has become a common practice during last years. RTA furniture, also known as flat-pack, knock-down (KD), do-it-yourself (DIY), self-assembly, or kit furniture, is an approach in furniture design that lets the end
user take on the task of assembly by themselves. This way, both the producing company and the customer benefit of lower costs, transport efficiency and more versatile products. Furthermore, environmental sustainability is enhanced due to a more efficient delivery and avoiding the use of machinery for assembly. This is why RTA principles are going to be a central part of this project, and the furniture resulting from it is intended to be assembled by the end user.

Ready to assemble furniture is a common trend especially in European market, with companies such as Dorel, Ikea and Tvilum. The main reasons for the growth in this market are the great number of customers wishing to save money by assembling the products themselves, and the efforts done by the companies of providing affordable products, taking into account the necessity of making the task of assembly as easy and comfortable for the user as possible. RTA furniture market in Europe is expected to grow at a CAGR (Compound Annual Growth Rate) of 4.11% by revenue during the period 2016-2020 (PR Newswire, 2016).

Taking into account this data, it is obvious that the RTA Furniture market is competitive and companies struggle to come up with designs that guarantee an easy assembly without sacrificing functionality, durability and aesthetics. To be able to differentiate from other designs in the market, this project takes into account DFA and UXD principles to guarantee an optimal assembly for the user.

### 2.1.5.2 Scandinavian Design

The design of the set is mainly based on Scandinavian design characteristics due to the philosophy and guidelines (see below) why this design style is so famous. The items designed within this style are mainly aimed for the well-being of people, keeping in mind at the same time of environment and economy. Same subjects like the set intend to include.

Modern Scandinavian design was born in the 1930s, although the first time the term “Scandinavian design” is known was during the 1950s (Lucano, 2016). This design influence was carried out in the five Scandinavian countries: Norway, Sweden, Finland, Iceland and Denmark. Each one of them developed their own approach, although all of them share the same philosophy. This philosophy is based on the following principles:

- **Practical outlook**, functional products whose main goal is to improve the quality of the daily life.
- **Social conscience**, affordable products for everyone, also known as democratization of design.
- **Respect for the environment**, it is the most basic characteristic of Scandinavian design. Since the raw materials are limited in the Nordic countries due to the extreme weather and the geographic isolation, their natural resources must be carefully managed.
- **Aesthetic sensitivity**, trying to reflect on the products natural references, such as flora and fauna or whatever related to nature.

The emphasis about the quality of the daily life it is a consequence of the Nordic weather which is very harsh in winter - very cold, with shorts days and little light. That is why Scandinavian people spend most of the time at home. So, it is very
important to create a warmth atmosphere to enjoy with family and friends. This is called "Hygge" (Fiell and Fiell, 2013), it is a Danish concept which evocates coziness and wellbeing at home. The products designed within a "Hygge" view should make the stay at enjoyable in order to make more bearable the hard climatic conditions (See figure 16).

To contribute to the comfort for a domestic environment, the materials should be chosen and treated carefully, respecting the nature, due to the shortage of raw materials. The material most used is the wood, but also the leather or sheep or reindeer skin and ceramics are used quite often.

![Figure 16: Interior with a Hygge concept (How To Hygge: Embrace the Cosy Danish Concept, 2017).](image)

As it is stated previously, Scandinavian Design principles will be kept in mind as guidelines to follow along the design process. On one hand, the function of every characteristic of the set, none of the parts is added randomly. On the other hand, the material to build the set will be chosen taking care of the environment and providing an aesthetics that reflects this aim.

### 2.1.5.3 Tendencies

Currently, industrial design has a strong environmental commitment and awareness. Even so, this issue has to enhance, that is why the role of the designer should take charge of this responsibility in order to encourage successfully the importance of sustainability.

As it is known Scandinavian design philosophy suits sustainable and environmental principles. Definitely, its most remarkable example is IKEA (Sweden, 1943) whose ethic relies on good and democratic design. To go for this goals, IKEA was the first company that introduced the self-assembly furniture and also the company created the concept of modular system achieving by flat packs. Recently, IKEA has launched the Lisabo serie (See Figure 17), the main characteristic of this range of tables and desks is that the wedge-dowel concept (created by the company) is applied to the legs. It consists of the leg just slides into place and it is locked in with a single screw that holds the wedge. This concept
helps to save extra raw material, extra things for a manufacturer to ship and extra things to assemble.

Figure 17: Lisabo serie

Similar examples that deal with sustainable methods, especially ecological assemblage, have taken place at the Stockholm Design Week 2017. Regarding to the assemblage, there is one sort of assemble which requires extra pieces (See figure 18). On the other hand, the same pieces of the product fit together between themselves (See figure 19).

Figure 18: Items of furniture where the fasteners are wooden pieces
Other interesting manners to assemble less conventional with ropes (See figure 20), but good to take into account, since some insights can be came up from these concepts and ways to join.

Apart from the way to assemble, there are another alternatives to design sustainable products, for instance, regarding to the material selection. The best examples to talk about this is the Mirra chair (See figure 21) by Herman Miller. The 94 % of the material that this chair is made of is recyclable achieving also a good ergonomic shape (Kem-Laurin Kramer., 2012).
2.1.5.4 Moodboards

A Mood Board (Ambrose & Harris, 2010) is a sort of collage which is very helpful tool in order to get some inspiration, gathering random inputs that might come up with some ideas. These inputs can be whatever either photos, words, text or materials, as long as they are related to the product. The main purpose of this method is to get to know which aspects are to be wanted to convey through the product.

The images collected in the first Mood Board (See Figure 22) are related to some themes that somehow might have an influence on our product. Some of them are about some examples of Scandinavian interiors in order to figure out how both stool and table should look like, words that remind some concepts that both pieces of furniture have to represent or about ways to assembly without extra fasteners to get some inspiration.

![Figure 22: Mood Board number 1](image)

The following Mood Board (See figure 23) is made out with furniture items which mainly follow interesting assembly principles.
2.1.6 Material research

Even though the product is still not designed, it is advisable to conduct an initial material research to gain a better understanding of which materials are more suitable for the kind of product which this project aims to produce.

Metals
Metals could be a good choice for the material due to their general strength, rigidness and ductility (Cuffaro, 2013). They are usually easy to conform and can adopt shapes that are impossible for other materials by being casted or wrought. Also, metals present a high recyclability compared to other type of materials. More specifically, steel and aluminum have the best figures when it comes to recyclability, with more than 40 percent of steel and 35 percent of aluminum being composed of recycled material (Lawson, 2013). These two metals are usually alloyed with other components in different percentages to achieve different material properties.

- Aluminum alloys are composed of aluminum, which comes from bauxite, a quite common ore in the world, and other metals. It is alloyed because of the lack of
mechanical strength of aluminum in comparison with steel. Alloyed aluminum usually loses some corrosion resistance, which could affect negatively to the product, due to the fact that it is likely that it is going to be in contact with liquids, and it is something that should be looked into before choosing it as part of the product. Despite of this, aluminum is an interesting material mainly due to the abundancy of recycled aluminum, mainly since the recycling process for aluminum only consumes 5 percent of the energy consumed when it is extracted from the ore.

- Steel alloys are made out of iron and carbon and usually present better mechanical features. Even in their mild carbon variants they can be used for furniture making with successful result. They can be mixed with chromium to make it stainless so it can be used in more harsh environments such as bars or pubs.

Other metal alloys could also be considered, but they tend to be too difficult to recycle. For example, Titanium has excellent physical properties but its extraction is costly both in energy and in money.

**Plastics**

Plastics are used extensively in different production fields due to their generally low price, easiness of shaping and versatility. Furthermore, plastic variants are broad and can be adapted to almost any situation of usage. However, their sustainability is somehow a controversial matter. Despite the fact that many of these plastics can be recycled easily, even those which are most recyclable such as PETE, HDPE and PS are prone to suffer UV degradation over the recycling process (Badia, 2017). This explains the fact that only 5 percent approximately of plastic is recycled as raw material. Furthermore, plastic waste is one of the major problems in sustainability, due to the amount of consumption and the low recycled usage of it, and the processes by which they are manufactured are quite polluting. A pyramid showcasing the degree of danger each kind of plastic was published by the organization greenpeace (See figure 24):

![Figure 24: Pyramid which shows the pollution that produced different kinds of plastics.](image)

Therefore, a safe bet for the products if DFE needs to be guaranteed would be to opt for biobased polymers. This is furtherly supported by the fact that the rest of the plastics, called petroplastics, are based on fossil fuels. Bio-based polymeric materials are made for organic and renewable materials, normally plant cellulose. They suppose them cutting-edge technology in materials and currently they are the only renewable materials available for mass-produced
mouldings. An example of bio-based polymers that can prove useful for furniture production is Arboform, which is fully recyclable and compostable (Lawson, 2013).

**Wood**
Wood could be a right choice for the product due to its renewable (with the possibility of it being reused as tinder, compost, or for other pieces of furniture) and organic characteristics. Furthermore, it is an attractive material that has been used since the beginning of furniture production, and it is the choice of many furniture fabricants in the market, also due to great physical properties against bulking, compression and bending, that in some occasions can even surpass those of metal.

However, despite this impressive figures wood presents a sustainability problem which is excessive consumption. Even though some organizations aim to responsible sourcing, 75 percent of the timber in the world is used by only 20 percent of its population, leading to an irresponsible cutting down of trees that is increasing every year (Lawson, 2013).

The main problem is the consumption of hardwood due to the fact that tees from this botanical family take from 30 to 60 years to be fully grown and ready for use. It is necessary to opt for fast-growing soft woods to make timber consumption sustainable in the world.

Another problem of wood is the transport of it, which can prove to be polluting if the wood is brought from a far place of origin and/or manufacturing. Due to this, it is necessary to consider those woods that are endemic in the place of manufacturing and ideally commercialization of the product, in this case the Scandinavian Peninsula.

Taking into account these requirements (See table 1), some Scandinavian softwoods have been selected for consideration about usage in the product, and their characteristics have been analyzed (Lawson, 2013).

<table>
<thead>
<tr>
<th>Table 1: Table with different softwoods properties.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CHARACTERISTICS</strong></td>
</tr>
<tr>
<td>Douglas</td>
</tr>
<tr>
<td>Redwood (Scandinavian pine)</td>
</tr>
<tr>
<td>Spruce (Norway)</td>
</tr>
</tbody>
</table>

Apart from considering these options of more traditional woods with developed manufacturing techniques, it is interesting to consider bamboo as a material for the products. The main reason is the fast growing of this kind of wood and the fast developing of the industry revolving around its treatment and manufacturing, though there are not yet any low-cost laminated solutions. However, the transport of raw bamboo to manufacturing plants and after to the place of production might
prove costly and polluting, and it is something that should be looked into to determine its suitability.

**Cardboard**
Cardboard is an unusual material for material fabrication which has been gaining popularity over the last few years due to its alternative looks and environmental values attributed to it (Shimo, 2009). Often used as packaging, cardboard recyclability makes it one of the most common materials to be used in its recycled form, with 90% of U.S. packages being shipped in recycled cardboard. It is also biodegradable. Corrugated cardboard can be used in furniture due to its good physical properties against compression, its rigidity and strength. It usually comes from recycled sources and is more environmentally friendly than ever before, being able to be processed without bleaching. However, cardboard presents an important fault which is its inability to resist water when it is not covered by any other material. If it is considered that the products which this project aims to are prone to get in contact with liquids it should be mandatory to apply a resin or other covering substance to make it waterproof, which might prove quite expensive and contaminating, and it is a subject which should be looked into.

### 2.2 Empirical Studies
Here different studies conducted in regards of specifying the objectives of the project are covered. This data has a theoretical fundament but has been gathered by the design team by analysis of the problem as well as testing when it has been considered necessary.

#### 2.2.1 SWOT Analysis
In order to understand better the kind of constrains and obstacles that will be present in the project, an analysis (See appendix A) of the strengths, weaknesses, opportunities and threats. These points will be kept in mind to find a gap in the market in order to introduce the product successfully. In addition to this, SWOT is very helpful to generate feasible ideas according to the advantages to make the most of and the drawbacks to improve.

As conclusion, the worst issue collected from SWOT is the social lack of awareness about sustainable and its importance. Then the set might be not bought because customers may not appreciate the sustainable aspect on the set. Another disadvantage to encounter is the lack of material and tools. So the design will be adjusted according to the available resources. By last, the best side is the set’s scope which englobes many issues, such as packaging, user experience, DFA, DFE and so on, that ensure good sustainable properties to the product.
2.2.2 DFA

In this project, DFA use acquires a special importance due to the necessity of:
- Reducing assembly process costs and environmental footprint. This can usually be done by reducing number of joining pieces and the difficulty of the assembly.
- Ensuring an easy and fast assembly process for the end user, guaranteeing that the user experience is satisfactory.

Therefore, in this project it can be stated that DFA relates directly with DFE and UXD, and it is a basis of these other two. It is reasonable therefore that one of this project’s main objectives should be to guarantee a good DFA approach and, once the design is finished, to assess the suitability of it via suitable criteria.

A main part of this criteria is a measure of the assembly efficiency of a design called DFA Index (Boothroyd, Dewhurst and Knight, 2011).

2.2.2.1 DFA Index

This index takes into account both the number of parts in a product, the ease of handling, insertion and fastening of the parts.

\[ E_{ma} = \frac{N_{\text{min}} t_a}{t_{ma}} \]

This figure represents a theoretically ideal situation where \( N_{\text{min}} \) is the minimum number of parts, \( t_a \) is the time basic assembly time for one part (which is obtained with the average between each part’s time), and \( t_{ma} \) is the approximated time to complete the assembly of the product. It is necessary to have an idea of how high the DFA Index should be for the product before starting the generation part to have a good knowledge of the standards that have to be met in this regard.

For this, some results about assembly process preference regarding time and number of parts needed to be assembled have been taken from a survey conducted with a group of 74 people from 20 to 60 years old (see appendix A). This survey had questions about different aspects of the product but had a major focus on the assembly preferences of potential customers:

- Number of parts (\( N_{\text{min}} \))

For having a better idea of how many parts would preferably be assembled by the customers, they were asked how many pieces they would consider acceptable for the set. The results are shown in Figure 25.

![Figure 25: Diagram with the results of the question about number of pieces acceptable.](image-url)
Figure 25: Answers for the question “What would you consider an acceptable number of pieces for the assembly of set of high stool and table?” The results show how a great number of users consider that the ideal number of pieces is somewhere in between 10 and 20. Approximately half of the interviewees are knowledgeable in engineering in some extent, however it can be expected that some of the interviewees would not know the number of pieces for a normal stool or table, but this can be taken as an ideal number of pieces the project can be worked towards. For this reason, $N_{\text{min}}$ is going to be considered 15.

- **Total time of assembly ($t_{\text{ma}}$)**

For having a better idea of how much time a potential customer would be willing to spend in the assembly of the product, the same group was asked this question for a set of stool and table. The responses are shown in the following figure 26.

- **Time for each part ($t_a$)**

The basic assembly time for each part is a different matter, as it can be taken from any study such as a survey. This makes it somehow difficult to determine the average time it takes in a product to assemble an individual piece without any physical prototype to test it. However, some classification systems exist for arranging pat features which affect manipulation of the pieces such as the acquisition, movement, orientation, insertion and fastening of pieces (Boothroyd, Dewhurst and Knight, 2011). This systems take into account different characteristics of the pieces that is needed to be assembled and the way in which it needs to be done, including:
- Easiness of grasping.
- Need for tweezers or other tools.
- Flexibility and possibility of tangling.
- Screwing operations are needed or not.
- Easiness of alignment.

For this reasons, it is quite difficult to determine this value via these systems if the design is not done yet, due to impossibility of knowing the pieces’ characteristics. However, for exploration purposes, it has been considered that this value will be around $t_a=3$ seconds. It has been considered this way due to the fact that this is the average time for pieces which are of easy insertion and managed by one person without the need of additional tools (Boothroyd, Dewhurst and Knight, 2011).

**DFA Index ($E_{ma}$)**

Once the approximate values for all the different factors have been determined, it is possible to calculate a first approximation of the desired DFA Index.

$$E_{ma} = \frac{15 \cdot 3}{30 \cdot 60} = 0.025$$

It can be appreciated that the resulting DFA Index is quite low, considering that the ideal DFA Index would be 1. This means that it would be quite easy to fulfill this objective of 0.025.

It can be assumed that this is due to the consideration that the survey participants have to firstly understand the instructions and then assemble the objects. The DFA Index is merely a theoretical tool that does not take into account the reading of instructions and its difficulty, as well as some problems that the user might run into while assembling the product. It only takes into account the easiness of manipulation and grasp. Therefore, DFA Index is not going to be taken as base for the project DFA approach but as a figure for additional information.

**2.2.3 DFE**

As the title and specifications of the project dictate, one of the main objectives of the product is achieve a reasonable level of sustainability. This will be done by adopting a series of measures, which revolve mainly around DFE and DFA principles. However, before adopting these measures it is needed to analyze how the project can affect sustainability.

Sustainability is a rather broad term that includes environmental, economical, and social needs of society, both in the present and the future (Kramer, 2012). Rather than understanding the problem as merely factors that affect environment and nature, it is needed to integrate social, economic and environmental factors in such a way that the necessities of present and future generations are met.
That is why the sustainability factors in the project can be more complicated than it appears at first. With the objective of gaining a better understanding of the factors affecting sustainability in the project, all of them were listed down and related with the part of sustainability they affect. This analysis was made with the assistance of a seminar/workshop based in verbal interaction conducted on this matter in the University of Skövde.

2.2.3.1 Environmental sustainability

It can be understood that environmental sustainability comprises all the activities that ensure that human influence does not affect negatively the environment both in short and long term. It is important that these practices can be kept indefinitely, as it is one of the key points of sustainability. Every product development affects in one way or another environmental sustainability. For the current project it has been determined that they will be affected in these ways:

- Material extraction: raw materials need to be extracted from natural sources, which will affect inevitably the environment. Source depletion is a reality nowadays, and in the case of some materials, specially certain metals, it can be proved that, at the current pace of extraction, shortage will occur within a few years. Furthermore, extraction consumes energy, which will most likely come from fossil fuels. It is needed to take this into account to ensure that the extraction process is as sustainable as possible.

- Material recycling: it is known that recycled materials are a common choice in companies that want to improve their sustainability in products. However it is needed to take into account the recyclability of this product, the energy it takes to recycle and how polluting is the process. Sometimes it can happen that the choice of a recycle/recyclable material is not worth it due to the process behind it.

- Production: in production energy is consumed and pollution can be produced depending on the process. It is necessary to choose a process that is as harmless as possible to the environment, being still capable of conform the material.

- Assembly: during assembly materials are usually used due to the necessity of joining pieces. Materials are used for the production of screws, nails, bolts, rails, adhesives and other joining elements. Also, in some cases industrial processes such as welding are used for the assembly. In our case, sustainability in this process will be worked towards by the adoption of DFA principles that let the assembly task be done by the user in an uncomplicated way, getting rid of as many joining elements as possible and of all the industrial processes during assembly. Furthermore, disassembly and recovery of pieces is also an important matter (Fiksel, 1996).

- Packaging: one of the most common forms of waste is the packaging of the product. Packaging is mostly understood as a disposable object which has to go to waste once the product is extracted from it. Some companies go for more environmentally friendly packaging by using recycled materials and avoiding adhesives, or packages that have some added value, making it possible to keep the packaging as part of the product.
Transport: the distribution of the product is crucial for a successful product. However, transport is mostly done by vehicles which run on fossil fuels, making the transport a phase in which the environmental footprint of the product increases considerably (Kramer, 2012). It is necessary to reduce this footprint by decreasing weight and making it possible to transport as many products as possible at once, making the transport more efficient. This relates directly with the packaging, and distance of transport, which is going to be kept as low as possible by in-house production.

Disposal: the disposal of the product can have an important effect in environmental sustainability. This is why it is important both to increase the useful life of the product as much as possible and make the disposal of the product as harmless as possible, either by recyclable or reusable materials.

2.2.3.2 Economical sustainability

Economical sustainability can be defined as all the activities directed to maintain economic development without negative consequences for either the environment or social sustainability. Economic growth is obviously an objective of the project, as it is necessary that this product provides benefits for the company producing it. It is affected mainly by:

- Material extraction: the choice of materials will affect the costs of production and therefore the economic sustainability of the product. There is a necessity to consider the costs of extraction or acquisition of raw material.
- Material recycling: while there are cases where the recycling of material might be a more economical choice, it is necessary to consider that in some cases the material can be more expensive if it is recycled due to the processes behind it.
- Production and assembly: these processes can be quite costly depending in the industrial processes chosen and the materials where they are applied. In this case assembly costs will be reduced drastically as the assembly task will fall on the end user.
- Commercialization: ultimately, this is the phase where the economic sustainability will be tested. It is necessary that this phase provides positive economic growth or the product will be considered a failure.

2.2.3.3 Societal sustainability

This field of sustainability aims to achieving goals related with human factors such as integration, safety, equality, life quality, culture, etc. Often considered a secondary aspect of sustainability, it is actually an important factor in global sustainability. It is affected mainly by:

- Production: it is necessary to take into account the risks and harshness of tasks during production, that workers have to assume.
- Assembly: the difficulty of assembly will affect the end users, as they will be the ones doing this task. That is why DFA and UXD principles are going to be applied, in order to make assembly uncomplicated.
• Commercialization: it is an important part of the product regarding social sustainability, as it will determine whether the customers accept the product or not. Factors such as ergonomics, adaptability, durability and quality play an important role here. Accident prevention is also a key aspect (Fiksel, 1999).

• Disposal: this stage of the product also affects social aspects of the product as its recyclability and the easiness of it will affect the customer and his view towards it. User’s perception of the ecological value of the product and its durability affect greatly their alignment with the company producing it (Kramer, 2012).

### 2.3 DESIGN SPECIFICATION

After analyzing the different aspects that will affect the success during the pre-study, it is possible to create a requirement list, according to the problem statement. This requirement list (See table 2) will serve as a necessary goals list that will help evaluate the proposed alternatives during the proposed schemes phase.

These goals were classified as demands (D) or wishes (W). Demands are mandatory and wishes are additional goals that boost suitability.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Demand (D)</th>
<th>Wish (W)</th>
<th>Unit</th>
<th>References/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>Stool</td>
<td>Table</td>
<td>kg</td>
<td>Comfortable range for furniture (Lawson, 2013).</td>
</tr>
<tr>
<td></td>
<td>&lt;8</td>
<td>&lt;15</td>
<td>&lt;6</td>
<td>&lt;8</td>
</tr>
<tr>
<td>Durability against fatigue</td>
<td>10.000</td>
<td>100.000</td>
<td>Cycles</td>
<td>Engineering standards.</td>
</tr>
<tr>
<td>Stability</td>
<td>Able to stand</td>
<td>-</td>
<td>-</td>
<td>Without additional forces.</td>
</tr>
<tr>
<td>Strength</td>
<td>F.S = 1.5</td>
<td>F.S = 3</td>
<td>-</td>
<td>Engineering standards.</td>
</tr>
<tr>
<td>Ranges of measures</td>
<td>Stool</td>
<td>Table</td>
<td>mm</td>
<td>Comfortable for high stool and table (Lawson, 2013).</td>
</tr>
<tr>
<td>Height</td>
<td>590-740</td>
<td>890-1040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>450-550</td>
<td>&gt;450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>200-400</td>
<td>&gt;450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>As needed</td>
<td>&lt;30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot rest</td>
<td>200-250</td>
<td>250-350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity resistance</td>
<td>No damage</td>
<td>Imperbeality</td>
<td>-</td>
<td>Evaluated by material characteristics.</td>
</tr>
<tr>
<td>Packaging sizes</td>
<td>1200x800-1200x1000</td>
<td>-</td>
<td>mm</td>
<td>EU, EEUU and Japan standards.</td>
</tr>
<tr>
<td>Pieces production</td>
<td>In-house (Tibro)</td>
<td>-</td>
<td>-</td>
<td>To minimize transport.</td>
</tr>
<tr>
<td>Raw materials radius of location</td>
<td>100 around Tibro</td>
<td>-</td>
<td>km</td>
<td>To minimize transport.</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>300</td>
<td>150</td>
<td>MJ</td>
<td>ISO 14000</td>
</tr>
<tr>
<td>Tolerances</td>
<td>Lawson, 2013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recyclability</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disassembly</td>
<td>No breakage of parts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pieces</td>
<td>&lt;15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum time of assembly</td>
<td>&lt;30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cognitive ergonomics (failure rate)</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simplicity</td>
<td>No extra fasteners</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foot rest</td>
<td>In stool or table</td>
<td>Both of them</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrity</td>
<td>Can be moved</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Packagings %</th>
<th>ISO 14000</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disassembly %</th>
<th>ISO 14000</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of pieces</th>
<th>Pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;15</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum time of assembly</th>
<th>Mins.</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cognitive ergonomics (failure rate)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simplicity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No extra fasteners</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foot rest</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>In stool or table</td>
<td>Both of them</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Integrity</th>
<th>Moving without falling apart</th>
</tr>
</thead>
</table>
3 CONCEPTUAL DESIGN

Once the list of requirements is specified, a phase of conceptual design follows. In this part of the report the different results from the methodology followed for the concept generation are gathered and presented in such a way that the idea flow can be understood and followed.

3.1 Concept ideation

The first part of the generation phase consisted in bringing up as many ideas as possible with the intention of having a good number of concepts to choose, combine and evaluate.

As stated previously, this project has a great focus on optimizing the assembly processes and making it intuitive and attractive for the user, so it made sense that the first focus of the generation was the joint types, exploring different shapes, directions and processes to join the pieces without any additional screws.

The previous statement is conducted together with the limitations which have been set by the company. These kind of guidelines mostly deal with the aesthetic aspects, such as the integrity of the set which have to be very clear, making sure the stool and the table belong to each other through an appearance which both the stool and the table share similar characteristics. In addition to this, the design set should be feasible to build according to the resources and tools available.

This phase of generation was carried out using brainstorming techniques, combining mainly the NHK and 365 methods. The reason why these methods were chosen was because there was a need of generating a good number of proposals, and both these methods guarantee that the iteration of ideas will be fluid and varied, a basic need at this point of the project (Curedale, 2013).

Figure 27: Some of the different joints generated in this phase.
The complete results of this phase are gathered in Annex: joint generation results, in case they are needed for inspection. After a great number of these alternatives (See figure 27) were generated, the next step towards concept generation needed to be taken, which consisted in combining them in such a way that a final concept would be the result.

### 3.2 Combining alternatives

An essential step in concept generation is to combine different alternatives. An useful and thorough method to do so is the creation of a morphological chart. As stated previously in the method explanation part, a morphological chart (See table 3) is analytical generation method that is meant to serve as comprehensive figure containing all the possible solutions to the sub problems presented to the product (Cross, 2008). This was carried out by analysing the solutions that can be adopted primarily, making sketches of the parts when considered necessary.

<table>
<thead>
<tr>
<th>Table 3: Morphological Chart.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
The product is held in place during assembly

The product can be picked and moved around without falling apart

The product can be picked and moved around without falling apart

Provide sitting surface

Foot rest

This morphological chart can be considered a base for idea generation, as it comprehends all the possible alternatives for each part, making it possible to create a great number of combinations choosing each one of them.

### 3.3 Final material choice

The final material choice was not done until the design shapes were mostly defined, as it was necessary to know if these shapes were feasible for certain materials.

When it was clear what kind of geometry would be necessary for the joints, it was decided that wood would be a suitable option, specifically spruce wood. This material was chosen over others because of the excellent down recyclable, reusable and biodegradable characteristics of wood in general, and the good mechanical properties of spruce specifically.

### 3.4 Critical success factor chart

The first evaluation method was used to narrow down from a great number of alternatives that were created during the design phase. This was done by evaluating if the minimum demands were met.

The method used for this was the critical success factor chart. This method consists in, firstly, to list the critical success factors of the product, which are the necessary factors or characteristics that this product needs to have in order for it to be considered successful, the demands in this case (Curedale, 2013).
Each of the proposed concepts were evaluated against demands. The performance in each demand was in occasions considered in an approximate and subjective manner, as the concepts were too many and too varied for a thorough analysis of physical and specific properties. The performance for each demand was evaluated in a 3 point scale, where the minimum means the demand is not fulfilled, causing the concept to be rejected immediately.

The critical success factor itself is located in the annex in case it is needed for further analysis.

3.5 Final concepts

After considering the delimitations and demands imposed by the company and carrying out a preliminary evaluation phase based on a critical success factor chart, the number of concepts was narrowed down to three. These concepts are the product of combination taking the morphological chart as a base, of different characteristics, and they are quite different from each other aesthetically, functionally and in assembly. As the final proposed concepts, these will be considered for further analysis and all the specifications for them will be obtained, so they can be evaluated more thoroughly. Here they are presented briefly along with their characteristics.

**ZETA CONCEPT**

This preliminary concept (See figures 28 and 29) is based on dovetail-system assembly process that would be carried out inversely by the user. This means that the table top/seat would be placed firstly on the floor upside down and the rest of the product would be built on top of it. Finally, the user would need to turn the whole piece of furniture around so it would be usable. The models also rely in a footrest (table) and on a base (stool) for guaranteeing stability and integrity if the pieces are to be moved around. Aesthetically, the concept refers to the purity of lines and geometrical preference in modern Scandinavian interiors.

Figure 28: Zeta concept sketch.
TRIPOD CONCEPT
One of the boldest concepts in terms of assembly methods and structure geometry, the tripod concept (See figures 30 and 31) relies in a system of insert-and-turn assembly as well as geometry aspects which make the pieces fit together. These characteristics make this concept stand out for the reduced number of pieces, which would be assembled reversely for the table and in standard order for the stool, as the legs would go first and the seat would be mounted on top.
One of the legs in the stool also acts as a footrest.

Figure 29: Zeta concept render.

Figure 30: Tripod concept sketch.

Figure 31: Tripod concept render.
SQUARE CONCEPT
This concept (See figures 32 and 33) is the most simple regarding the geometry and the way to assemble in comparison with the two previous ones.

This set consists of the system called “falling into pieces” and it is just about sliding one piece into each other. The position to manage the assembly is to lie down all of the pieces and just slide one piece onto other one.
Moreover, both the stool and the table share something in common and it is the kind of handle on the top in order to allow an easy grip and take the pieces of furniture to one place to another without falling apart.

Figure 32: Square concept sketch.

Figure 33: Square concept render
4 EVALUATION

Once all the remaining concepts are proved to meet the minimum demands of the product, it is time to evaluate them using more in-depth methodology. Demands are also evaluated assuming that their minimum is met, but when a concept performs better regarding a certain demand it is taken into account for the final choice.

4.1 Weight

One of the characteristics that the product needs to fulfill is a weight limit that it needs to be under for guaranteeing a good handling of it. The weight calculations (See table 4) were made parting from the CAD model and taking into account the volumes of all the different parts of each model and wood density.

<table>
<thead>
<tr>
<th>SET</th>
<th>Stool</th>
<th>Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>3.66 kg</td>
<td>9.55 kg</td>
</tr>
<tr>
<td>Zeta</td>
<td>6.68 kg</td>
<td>7.73 kg</td>
</tr>
<tr>
<td>Tripod</td>
<td>4.63 kg</td>
<td>14.8 kg</td>
</tr>
</tbody>
</table>

Table 4: weights of the components of each set of furniture.

4.2 Stability

Stability is a basic characteristic for every piece of furniture. However, it can be quite difficult to determine without real prototypes. In this project, an initial approach was to follow static physics theory and determine the degrees of freedom of the structure by analyzing it. If the result of the static determination grade is below 0, it would mean that the structure is mechanism and therefore not stable (Uicker, Pennock and Shigley, 2003). The results obtained from this approach were that all of the concepts were statically stable.

For the models that were considered more prone to be unstable, scaled mockups (See figure 34) were built in order to test the stability with a more empirical approach.

Figure 34: scaled mock-ups for testing the stability of the tripod stool (1/4 scale), zeta table (1/7 scale) and square set (1/7 scale).
Mock-ups showed that all of the concepts had an acceptable level of stability, but some of them could be improved.

- Square concept showed a tendency of bending due to bulking, which could lead to the legs falling out of place, therefore an additional supporting structure would be a good idea.
- Zeta concept showed a risk of disassembly if the piece is lifted, due to the lack of a vertical force that ensures.

4.3 LCA

Environmental sustainability is of great importance in any modern product design concept. However, in this project, because of the objectives and specifications stated earlier, it obtains a new dimension and becomes one of the most relevant factors. Given this, it is necessary to make a thorough analysis of the environmental footprint of the product, considering both resources taken and waste generated. For this end, the method used has been a Life Cycle Assessment (See figure 35).

Firstly, all the different steps that the product will go through during production, usage and end of life situations. This analysis has been done as thoroughly as possible with the available information, taking into account the locations, industrial processes and commercialization.

![Figure 35: graph showing the different phases which that the product will go through in its life cycle.](image)

The raw material, as stated before, is spruce wood. This will be obtained from several sources across Västra Götalands county in a sheet format which is ready for manufacturing. From these sources it will be transported to the manufacturing plant located in Tibro. The product could be sold in several locations in Sweden and Norway, trying to avoid long distance transport and keeping it a local product
exclusive to the Scandinavian market. The end of life is considered either repurposed, downcycled for spruce wood.

Considering the figures for transport distance, industrial processes and material cost of extraction, a LCA (Life Cycle Assessment) was performed for each of the three concepts. Once the results were obtained, they were compared.

As can be appreciated in the graph (See figure 36), the main energy usage comes from the material, including raw extraction and conforming in sheets. It is no surprise then that the best result is obtained by Square set, as it is the set which uses the least material.

Figure 36: graph comparing the three sets performance regarding energy usage.

Figure 37: graph comparing the three sets performance regarding CO2.
If the CO2 Footprints (See figure 37) of each of the three concepts are compared, the material quantity is again a big factor, and the best result is obtained again by Square set. The figures obtained by each of these sets are gathered with further detail in the annex if there is a need for analysis.

4.4 Easiness of assembly

As stated previously, the easiness of assembly is a requirement in this project due to the necessity of guaranteeing a satisfactory user experience.

It was determined that the easiness of assembly needed to be tested empirically by user tests because of the lack of reliable tools that quantify the easiness of this process. The user tests were mainly focused on cognitive ergonomics. This means that the factor that was majorly tested was the ability of the subjects to recognize the direction and process of assembly, mainly by three factors:

- Time that took each of the users to consider each joint assembled.
- Ability to join the piece successfully.
- Subjective experience of each user, based on impressions during the test and questions answered after it.

The mock-up joints were printed in 3D using PLA plastic, and presented pair by pair to the users, which belong to a population of 20. For each of the five different joints, the time was taken and notes were taken about the ability of the users and the difficulties they encountered.

The participants are asked to think out loud and speak up their impressions and feeling while they are figuring out how to fit together the different pairs of pieces. In addition of these several thoughts, the reactions and the actions that all of the participants do are also gathered in order to see the performance of assembly and the way to recognize how each piece is positioned by the participant to get together with its partner. The picture marked in green indicates correct assembly, and in red an incorrect one.

**Joint 1**

This joint (See figure 38) has been assembled successfully by all of the participants due to the geometry which is easy to see and it makes clear how both pieces should be together. Furthermore, all the participants are sure when they finish to assemble both pieces.
Joint 2
Regarding this joint (See figure 39) has been performed properly just by a few of participants. Most of the cases, they are not sure if the assembly is well done, they introduce one piece into the other on the upside down or they think the joint is right when actually it is not.

Joint 3
Like the previous assembly, this pair (See figure 40) has some troubles to put together both pieces. The main reason is because of the hole which is hidden in one of the pieces, so it cannot been seen easily its orientation in order to slide one of the pieces into the other. So, the participants just try several times until they manage to assemble them.

Joint 4
The fourth joint (See figure 41) seems easy to put together, but it has been just a few who do it properly to the first. Normally, this pair has been assembled on the other way round twice and then they get them together successfully.
Joint 5
The upcoming joint 42 has been successfully by all of the participants, they do not hesitate about how to join the pieces and they are sure when they are done.

The conclusions that can be got out of these qualitative results are that the most suitable joints are 1, which belongs to zeta concept, and 5, which belongs to 5 concepts. The same conclusions can be extracted from the quantitative results, if the average and standard deviation of the time (See figures 43 and 44) are looked at.

![Figure 43: average and standard deviation for each of the times of assembly.](image)

Even though the average of the time in joint number 5 is quite high, it is most likely due to the presence of three pieces and the low tolerance between them, as many users expressed. A low standard deviation indicates a regular assembly process, indicating that it proves intuitive and easy for the users.

The number of times the joints were failed to be assembled was also compared with the number of times they were chosen to be difficult joints.
A close relation between these two values indicates that it is likely that a good number of these users knows that they failed to assemble the joint, and would likely try again to do so if they did not have the pressure of a user test.

4.5 Strength analysis

As the main finality of the set is to support body weight or objects placed on top, these products are required to withstand certain forces.

In these section, the performance of the concepts regarding this is studied and assessed.

4.5.1 Punctual force analysis

In this section of the project, the performance of the concepts against a punctual high force is tested by strength analysis of structures.

The focus in here is to guarantee that the product will withstand whatever weight it is applied during its lifetime without significant deformation or failure. For this reason, the force values that have been selected are much higher that the estimated forces that the piece of furniture is likely to withstand during its lifetime. These weights are of 115 kg and 80 kg for the stool and the table respectively.

The performance of the piece of furniture against these strains is going to be addressed by applying a factor of safety, which will be at least between 1.5 and 2, however ideally it will be above 3 to guarantee the security:

\[ F \cdot S = \frac{\rho_{adm}}{\rho_{eq}} \]

With a value of \( \rho_{adm} \) of 40 MPa for spruce wood. The value of equivalent tension \( \rho_{eq} \) in the system is obtained by the equation:

\[ \rho_{eq} = \frac{M_{z-max}}{W_z} \]
Where $M_{z_{-max}}$ is the maximum flexor moment in the system. This will be obtained by conducting a strength of materials analysis in the system, which will be carried out and with the structural analysis software RESMAT (See figure 45).

$W_z$ is the moment of inertia, obtained looking at the geometry of the section where the maximum moment is present and using its respective equation, as listed in table 5.

Table 5: Moments of inertia for different sections (Singh, 2014).

Upon the application of these principles, several results were obtained for the different concepts considered. These results (See table 6) were considered according to the value of each of the factors of security. A factor of security bigger than 3 is considered optimal, a factor of security between 2 and 3 is considered acceptable, and a factor of security below 2 is considered insufficient.
The results show that the best performance against punctual forces is done by the square set. They also determine that the tripod set stool performance is insufficient and there is a need for a change in one of the section’s geometry. Even after doing these changes, it is not advised to use this model due to the presence of high forces that can lead to catastrophic failure.

### 4.5.2 Fatigue analysis

One of the most important characteristics regarding furniture performance is the toughness against fatigue. When a piece of furniture deteriorates or fails, it is very common that it is due to the repetitive application of strains during the course of its useful life, rather than because of the apparition of a punctual high force.

Given this, a fatigue analysis has been carried out in order to guarantee that a good fatigue resistance is achieved. The analysis has been done theoretically because of the lack of necessary equipment and materials to be carried out with real tests. However, a thorough application of fracture physics guarantees the validity of the analysis.

The analysis has been done considering a weight of 70 kg and 30 kg applied vertically to the stool and the table respectively, during 10000 cycles of application. The fatigue test is going to be carried out considering simply the material used with no attention to geometry. The reason for this is the fact that, at level of small deformations, the geometry does not play a big role, with the fatigue resistance being affected mainly by tensions and material characteristics. Parting from this specifications, the fracture toughness of the material was obtained (Keunecke, Stanzl-Tschegg and Niemz)

\[
K_{IC} = 0.46 \text{ MPAm}^{1/2} \\
K = 1.12 \rho \sqrt{\pi a}
\]

Where \( \rho \) is the tension applied to the section and a maximum crack size. From this equality the maximum crack size supported by the material can be obtained. Once it is obtained, Paris Law is applied:

\[
\frac{da}{dN} = C \Delta K_m
\]

Where \( da \) is the variation of the length of a crack in the material, \( dN \) is the number of cycles, \( C \) and \( m \) material constants of value \( 1.16 \times 10^{-10} \) and 3 respectively, and

<table>
<thead>
<tr>
<th>Concept</th>
<th>Stool performance</th>
<th>Table performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>Optimal</td>
<td>Optimal</td>
</tr>
<tr>
<td>Zeta</td>
<td>Acceptable</td>
<td>Optimal</td>
</tr>
<tr>
<td>Tripod</td>
<td>Insufficient</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

Table 6: Depiction of each of the model’s performance in the analysis.
K the fracture tension, whose equation was previously stated. If these two equations are combined, the result is as follows:

\[
\frac{da}{a^{3/2}} = 9.07 \times 10^{-10} \times \rho \times dN
\]

After integrating on both sides of the equality, an equation defining the size of the crack after the cycles have finished is obtained.

\[
\frac{1}{\sqrt{a}} = 9.07 \times 10^{-10} \times \rho \times N
\]

If after applying these equations, the number of cycles N is bigger than 1000, the results are considered positive and the model will stand the fatigue it is applied.

4.6 Packaging

Packaging is an essential issue which strongly contributes a product becomes more sustainable, making it cheap, using as less material (cardboard, plastic, cork, tape, and so on) as possible, also taking for granted that all of them can be recycled afterwards. Regarding the package size, it should be the minimum required, to achieve it, the set aims to be packed in flat layout, in addition to make the most of the space and as a consequence reduce the use of transport. In addition to this, a suitable size and a proper shape enable an easy handle by users to carry the set either on pallets or manually.

In order to guarantee all of these targets every packaging of each proposal has been shaped in 3D models (See figures 46-48) in order to see clearly how they look like and how to manage the layout and position of the pieces to make sure a flat package.

Figure 46. Packaging n° 1

Figure 47. Packaging n° 2
Moreover, some measurements such as the depth, the length and the height (See appendix) are taken in order to get the volume and figure out how much space each packaging takes (See table 7).

Table 7. Packaging measurements and volumes.

<table>
<thead>
<tr>
<th>Packaging</th>
<th>Depth (cm)</th>
<th>Width (cm)</th>
<th>Height (cm)</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.3</td>
<td>81</td>
<td>104</td>
<td>137311.2</td>
</tr>
<tr>
<td>2</td>
<td>14.5</td>
<td>80</td>
<td>113.5</td>
<td>131660</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>88</td>
<td>97</td>
<td>128040</td>
</tr>
</tbody>
</table>

As the table shows, it can be seen that the first kind of packaging is the one with the biggest size. On the other hand the third packaging is the one with the smallest volume.

4.7 Weighted objectives

For the final choice of a concept, the data gathered from the previous analysis was introduced in a weighted objectives chart.

The process for the construction of this chart (See figure 49) went through different phases. Firstly, the objectives stated in the specifications table were ranked according to criteria established by the company and the product’s characteristics. The objectives were ranked and weights were assigned to them by systematically comparing pairs of objectives in a chart, according to a methodological approach to this problem (Cross, 2013).
This evaluation is not to be confused with an evaluation against demands, as this was carried out previously in the project and the concepts were proved to fulfill the minimum score regarding demands by the critical success factor chart. This evaluation aims to determine which of the concepts is more able to fulfill the wishes using a five point scale, where the results can be slightly above demands (0), above demands (0.25), quite above demands (0.5), near to wish (0.75) or wish (1). The exact figures for each objective were obtained using the product specifications.

The performance of each of the concepts was introduced in the charts (See table 8) and the final grade for them was obtained.

### Table 8: Weighted objective chart.

<table>
<thead>
<tr>
<th></th>
<th>SQUARE</th>
<th>ZETA</th>
<th>TRIPOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Performance</td>
<td>Final grade</td>
</tr>
<tr>
<td>LCA</td>
<td>0.09</td>
<td>0.75</td>
<td>0.0675</td>
</tr>
<tr>
<td>Dissassembly</td>
<td>0.036</td>
<td>1</td>
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<tr>
<td>Number of pieces</td>
<td>0.07</td>
<td>0.75</td>
<td>0.0525</td>
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<tr>
<td>Assembly</td>
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<td>0.75</td>
<td>0.0225</td>
</tr>
<tr>
<td>No extra screws/fasteners</td>
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<td>1</td>
<td>0.1</td>
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<td>0.075</td>
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<tr>
<td>Weight</td>
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<td>0.04</td>
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<tr>
<td>Fatigue</td>
<td>0.07</td>
<td>0.75</td>
<td>0.0525</td>
</tr>
<tr>
<td>Force</td>
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<td>0.05</td>
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<td>0.07</td>
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<tr>
<td>Integrity</td>
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<td>0.25</td>
<td>0.02</td>
</tr>
<tr>
<td>Stability</td>
<td>0.08</td>
<td>0.75</td>
<td>0.06</td>
</tr>
</tbody>
</table>

As can be appreciated in the chart, the best overall result is obtained by Square concept. It is also the most equilibrated one, so it is assumed to be the best of the three proposed concepts.
5  Detail design

The evaluation made it clear that, according to the criteria that were being used, the most suitable concept was Square concept, obtaining a good score in mostly all the important objectives.

However, it had a series of characteristics that could be improved. That is why a detail design phase was started, in which the design was polished.

5.1  The integrity and stability issue

Square concept obtained a low score in stability and integrity in comparison with other objectives due to some problems that were found out after mock-ups were constructed. The company, even though it was pleased with other aspects of the concept, also manifested its concern about this.

This issue was derivate from the fact that the tolerances could not hold together the structure after a certain deformation threshold was reached, as test showed, and another element needed to be used in order to guarantee the object would not fall apart.

Brainstorming sessions (See figure 50) in collaboration with the company were conducted aiming to reach a solution for this matter, combining dialogue and sketching.

Brainstorming sessions (See figure 50) in collaboration with the company were conducted aiming to reach a solution for this matter, combining dialogue and sketching.
At first, it was decided that a thin wood sheet was the element that would hold together the furniture (see figure 51). However, the construction of a physical prototype in real scale showed that this element was not as useful as it was thought to be. After going back to the drawing board, it was determined to try a new assembly method. This was tested in the final prototype (See figures 52 and 53), yielding good results in stability. Therefore, this was the final solution.

Figure 52: Final prototype stool  
Figure 53: stool testing at exhibition.

5.2 Optimizing material usage

Even though Square concept obtained good figures in LCA, it was noted that it could be made even more sustainable if the material usage was optimized.

The approach to this was done supposing that the raw material would be provided in 1500x800x27 mm wooden sheets, which is a standard format in which spruce sheets are usually provided in Sweden.

The flat and straight angled nature of the design of Square concept made it ideal for a good material usage optimization. Two different combinations (See figure 54) were evaluated.
The layout number 2 was eventually discarded due to two main reasons. Firstly, the layout required changes to the shape of the legs that would affect them, making them weaker to buckling. This also reflects in aesthetics (See figure 55), giving the piece of furniture an unstable look.

Also, after proceeding to calculations, the layout number 2 was found to be much more efficient at using material. Therefore, it was chosen for the final concept.

5.3 Other changes to the final design

Apart from the previously stated changes, some other final touches were prompted. The company expressed their wish for changing the armrests for a backrest for ergonomic purposes.

This backrest (See figure 56) was designed keeping in mind the need for integrity, using a side insertion with a locking by gravity. The backrest was located at 240 mm of height above the seat, following ergonomics studies on furniture (Lawson, 2013)
Also, for comfortability purposes, a piece of organic fleece was added to the stool. This material would be 90% biodegradable and provided by a retailer in Västra Götaland.

5.4 Final product

Once the detailing was finished and a satisfactory result was reached, the model was introduced in a CAD software and rendered for presentation (See figure 57).
The final model features a footrest that also acts as a piece that holds the pieces together. This is done by the insertion of a thin sheet of wood that prevents the legs from falling out of place.

As stated before, it also features a backrest of simple assembly. The backrest also contributes to the integrity because of its geometry.

The assembly process is unidirectional and intuitive, following the lines of the results of the user tests.

Figure 58: assembly process of the stool.

Figure 59: assembly process of the table.
6 Discussion

After looking back in the design process, it is easy to appreciate the fact that, even for a set of products in which the problem is apparently well defined, the design process can be difficult and full of wrong-way turns.

However, the fact that the project has followed a well-defined methodology from the very beginning has contributed to a good direction of the project even when there were unexpected changes and mistakes were made during the project. The great variety of concepts that were generated was a result of the different approaches that could be taken to the problem of a self-assembled and environmentally friendly piece of furniture. It proved a challenge to narrow down this number of concepts. However, a well-defined list of requirements and methodological approaches to decision making by convergent methods made it possible to narrow down these alternatives in such a way that the resulting ones had the best possible characteristics.

The dialogue with the company was constant and fluid during the whole design process, and the insight provided helped discard concepts that were not feasible in production or which did not fit what was expected from the project. User tests also provided good insight into how the final user would behave with the product and, what would be their preferences and capabilities when dealing with it. User testing was focused mainly in cognitive ergonomics, trying to guarantee an intuitive assembly. Unfortunately, physical ergonomics testing could not be carried out as planned, due to the lack of materials and tools to satisfactory build mock ups of all three alternatives that needed to be tested. It would be necessary to test these aspects if the product is taken into development in the future.

Physical building also proved to be a challenge, encountering problems that were unexpected, and making it obvious that, while everything works in CAD, real life models can behave in a different way.

Finally, it was also challenging to work for a company that was expecting results at the same time as having to fulfill certain requirements, given that the project is an academic thesis. At certain points in the project, there were conflicts of interest between the company, which was more focused in the results of the project, and the university, who had more interest in the methodology used. However, dialogue and collaboration led to a result that is hoped to be satisfactory for both parts.

In conclusion, the project has proved a challenging and thought-provoking work. It has offered the unique chance to put into practice the knowledge acquired in a more real environment with real requirements and specifications to fulfill. It has made more obvious the necessity of following a methodology in a product design project, still being open to changing strategy and going back to the drawing board if the circumstances require it.
REFERENCES


## APPENDIX A – SWOT Analysis

### STRENGTHS | WEAKNESSES
---|---
- Sustainable  
- Self-assembly  
- Low energy consumption of manufacturing  
- No glues, screws or any other complementary pieces  
- Environmentally friendly  
- Easy to use  
- Reusable and recyclable materials  
- Durability  
- Effective and efficient User Experience  
| - Some drawbacks to design the joints  
- Lack of proper tools to make prototypes  
- No manual instruction due to lack of time  
- No material supply from the company |

### OPPORTUNITIES | THREATS
---|---
- Availability of wide range of ecological joints  
- Minimum space to carry in order to reduce transport use  
- Easy to manufacture  
- It is not a seasonal nor fashionable product  
- Increase of environmental awareness  
| - Social unaware about sustainability  
- Products with similar proposals and characteristics in the market  
- Legislative laws |
1. What do you consider the most important factor when shopping for new furniture?

Others:
- The times and the reliability of delivery and then the price.
- Material and build quality.
- Round shape and looks.
- Comfortability.

2. Which environment would you relate with a set of high stool and table?

3. Have you previously assembled a piece of furniture from a DIY a line of products (ie. IKEA)?
4. If the answer is affirmative, what is the worst thing you have experienced during assembly?

5. What would you consider an acceptable assembly time (minutes) for a set of high stool and table?
6. What would you consider an acceptable number of pieces for the assembly of a set of high stool and table?

- Less than 5
- 5 to 10
- 10 to 20
- More than 20
- Other

7. Would the need of tools (screwdriver, wrench...) make you decide not to buy a self-assembled piece of furniture?
8. When using a set of high stool and table, how much time (minutes) do you spend usually?

- More than 60 minutes
- 30-60 minutes
- 10-30 minutes
- Less than 10 minutes

9. In general, do you find high stools comfortable enough?
10. What problems do you encounter regarding comfortability in these products?

- Shorter people having trouble to sit on them.
- Not possible to rest back.
- Backache after a while.
APPENDIX C – Complete creation process of joints

Figure B1: insertion from the side.

Figure B2: Vertical insertion
Figure B3: methods for keeping the assembly stationary.

Figure B4: two-movement assembly.
Square concept

Tripod concept
Zeta concept

CURVE Concept
Other concepts
## APPENDIX E - Critical success factor chart

<table>
<thead>
<tr>
<th></th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>Less material quantity</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
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<tr>
<td>Few pieces</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Stability</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Innovation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Feasible (production)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Packaged size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Easy to assemble</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Disassembly</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Ergonomic</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Reliable feeling</td>
<td>X</td>
<td>X</td>
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APPENDIX F - Weight Analysis for three resulting concepts.

Table F1: weight analysis for Square concept.

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<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Volume (cm³)</th>
<th>Weight (kg)</th>
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<tbody>
<tr>
<td>SEAT</td>
<td>Spruce Wood</td>
<td>0.43</td>
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<tr>
<td>LEGS</td>
<td>Spruce Wood</td>
<td>0.43</td>
<td>4012.12</td>
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<tr>
<td>FOOTREST</td>
<td>Spruce Wood</td>
<td>0.43</td>
<td>384.4</td>
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</table>

Total: 3.6642966

Table F2: weight analysis for Tripod concept.

<table>
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<th>Density (g/cm³)</th>
<th>Volume (cm³)</th>
<th>Weight (kg)</th>
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<tr>
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<td>LEG1</td>
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<td>Spruce Wood</td>
<td>0.43</td>
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</table>

Total: 4.638625

Table F3: weight analysis for Zeta concept.

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<td>Spruce Wood</td>
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<tr>
<td>BASE</td>
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</table>

Total: 6.680252
Figure G1: LCA Zeta concept.

Figure G2: LCA Tripod concept.
Figure G3: LCA Square concept.
APPENDIX H – User test paper

USER TEST 1 – ANALYSIS OF COGNITIVE ERGONOMICS ON ASSEMBLY

- Materials: 3D printed joints in the same color, disassembled, time measuring device, voice recorder.

- Parameters to measure:
  - Time of assembly (quantitative).
  - Ease of recognition of assembly direction and process (qualitative).

- Method:
  1. Pairs of pieces which belong together are laid disassembled.
  2. Before the subject is allowed to see the pieces, he/she is given instructions for performing the test.
     In this test, you are asked to join different pieces of furniture together. You will be given a pair of pieces at a time, and you need to assemble it. You need to let us know when you think a piece is assembled.
  3. The subject hands the paper where they will fill up their data and sign.
  4. One pair of pieces is presented at a time, while the rest of them are hidden and cannot be seen by the subject. When a piece is presented, the chronometer starts running.
  5. The chronometer stops running after the subject indicates that he/she considers the assembly finished.
  6. Once all the pieces are done, the test subject is handed another annex in which they are asked to fill out.
APPENDIX I – Assembly test user signature and questionnaire.

USER TEST 1 – ANALYSIS OF COGNITIVE ERGONOMICS ON ASSEMBLY

I hereby give my permission for the data collected in this test to be used for strictly academic purposes.

Signature:

---

USER TEST 1 – ANALYSIS OF COGNITIVE ERGONOMICS ON ASSEMBLY

- Which of the joints did you find especially difficult to join together?

1  3  5

2  4

- Which one of them was the easiest to join together?

1  3  5

2  4

- Any special suggestions on how to improve the joints?

__________________________

__________________________
APPENDIX J – Strength against punctual forces

- Tripod Concept.

\[ F = 1127 \, N \]

Most dangerous section: 4

\[ V_y = 1127 \, N \]
\[ M_y = 1127x \quad (0 \leq x \leq 0.06) \]
\[ M_{x\text{-max}} = 191.6 \]

\[ l_{xx} = 3.98 \times 10^{-4} \, m^4 \]
\[ \rho_{eq} = \frac{M_{x\text{-max}}}{W_c} \]
\[ W_c = \frac{c}{l_{xx}} = 2.65 \times 10^{-7} \, m^3 \]

\[ \rho_{eq} = 70.60 \, MPa > 40 \, MPa – \text{BREAKAGE RISK!} \]

Following, an analysis is carried out to find the measures that would guarantee the stool does not break under this force.

\[ \rho_{eq} \leq 20 \, MPa \]
\[ W_c - \frac{c}{l_{xx}} = \frac{4}{\pi R^4} \]
\[ 238.1 = R^4 \]
\[ \rho_{eq} \]
\[ R > 0.017 \, m \]

Once this necessity is found out, the necessary changes are done in the model to meet these needs.

- Zeta concept:

\[ F = 1127 \, N \]

Most dangerous section: 2

\[ N_x = 259.21 \, N \]
\[ W_y = 391.74 \, N \]
\[ M_{x\text{-max}} = 309.48 \, Nm \]

\[ l_{xx} = 7.3 \times 10^{-7} \, m^4 \]
\[ \rho_{eq} = \frac{M_{x\text{-max}}}{W_c} \]
\[ W_c = \frac{c}{l_{xx}} = 2.92 \times 10^{-5} \, m^3 \]

\[ \rho_{eq} = 10.6 \, MPa < 20 \, MPa – \text{SAFETY FACTOR IS MET} \]
Square concept:

\[ F = 281.75 \, N \]

The model is prone to fail by buckling, given the vertical geometry.

\[ P_{cr} = \left( \frac{\pi}{\beta L} \right)^2 E I_{xx} \]

Pinned bolt: \( \beta = 1 \)

\[ I_{xx} = 1.67 \times 10^{-7} \, m^4 \]
\[ P_{cr} = 596.7 \, N < 281.75 \, N \]

SAFETY FACTOR IS MET
APPENDIX K – Fatigue Analysis.

\[ K_c = 0.46 \text{ MPa} \sqrt{\text{m}} \]

\[ \frac{\Delta a}{\Delta N} = C \Delta K^m \]

\[ N = 1.26 \times 10^{11} > 10,000 \]

\[ K = 1.12 \rho \sqrt{a} \]

\[ a = \frac{0.52}{\rho^3} \]

\[ \frac{1}{\sqrt{a}} = 9.07 \times 10^{-10} \times \rho \times N \]

Therefore, the result is satisfactory.
APPENDIX L – Final Blueprints
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<th>N.º OF PIECE</th>
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<td>2</td>
</tr>
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<td>3</td>
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</tr>
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<td>4</td>
<td>BACKREST_STOOL</td>
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</tr>
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<td>CUSHION_STOOL</td>
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</tr>
<tr>
<td>6</td>
<td>Holder_stool</td>
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<td>4</td>
</tr>
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MODEL FILE NAME: STOOL_ASSEMBLY
DRAWING FILE NAME: STOOL_ASSEMBLY
SCALE: 1:10
DATE: 03/06/2017
APPROVED BY: Isabel María Guerrero Valadez
DRAWN BY: Alejandro Giul López
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<tr>
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<tr>
<td>4</td>
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