MANUFACTURING FOR CUSTOMIZATION

SYSTEM FOR FDM MASS CUSTOMIZATION BASED ON MONO-MATERIAL, TRANSFORMABLE INTERIOR COMPONENTS USING RECYCLED PET

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Acknowledgment

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GLOSSARY OF TERMS

FDM - Fused deposition modeling

PET - Polyethylene terephthalate (It is the most common thermoplastic polymer resin of the polyester family)

AM - Additive manufacturing

INTRODUCTIVE SUMMARY

The following report is an explanation to the process of identifying a relevant thesis topic, the literature research, design methodology and validation of the design task at hand. The literature research expands on the construction industry, PET as a single use waste material, Additive manufacturing, Fused Deposition Modeling and the design of an internal living module as reasons to further explore this project. As problems to be further explored, Transform-ability of mono-material printing, Design for manufacturing and assembly, Research by prototype, validation methodologies and the feasibility of FDM will be addressed. The above arguments will be followed by the problem statement and research questions described in detail. The design task will be identified and the design methodology specifically built to suit this design task will be explored in depth under the topic Methodology used for thesis validation. Each section will have a small summary of findings and relevance to this thesis explained. A few topics such as climatic conditions, sustainability, PET as a material were not explored further than that described in the literature research as they are already extensively proven topics of research.

One of the main outcomes of this thesis is that of an open source system of using additive manufacturing as manufacturing technique. Through an exemplary design, this project explores a physical trial and error evolution of a design without using predictive modeling. A system for anyone to evolve their design, prototype and manufacture without the need for experts could be suggested as a new wave for the maker movement; Mass customization for the masses,

A chosen design task will be an exemplary result following the careful incorporation of the methodology designed specifically for this thesis topic. The methodology allows for possibilities of being adapted for similar design tasks in the future.

The validation process of this design task will be heavily driven on functional and aesthetic bases. Prototyping will be used to validate the criteria directing this design task.

Conclusive points to be taken away from the research will be identified towards the end of this report along with the reflections based on methodology, research and design process. A further list of recommendations to extend this topic of research will be identified and suggested for future reference as design points.

All literature review references and any other references have been included.

1. BACKGROUND

A few topics as explained below were chosen to justify the need for this specific thesis topic. The following topics have not been extensively researched as they are already scientifically proven and extensive research has been conducted.

CURRENT ENVIRONMENTAL SITUATION

Climate change, rising sea levels, and polluted air quality are merely a few problems that have risen as a result of man-made pollution. According to the European Parliament statistics, in 2015, 322 million tonnes of plastic for utilization was produced in the world, in EU states 40% of this plastic is commonly used packaging mostly made of PET. 39% of this waste in EU states are incinerated, 31% disposed in landfills and only 30% is recycled (Europearl 2018).

In 2016, Netherlands itself produced an estimated 10 million tonnes of plastic packaging waste (Europearl 2018), Due to the high quantity of consumption, it has become vital that the maximum possible sustainability measures are carefully considered when designing and realizing any design as responsible architects and designers. In order to achieve an acceptable level of sustainability, industries must seek to move from a linear economy to a circular economy.

CONSTRUCTION INDUSTRY

The construction industry generated an unsustainable percentage of 36.4% out of 2538 million tonnes of all waste produced in the year 2016 in Europe (Eurostat), evidently in need of better disposal of construction waste or new and improved methods to challenge traditional construction techniques. Due to excessive consumption and discarding of material (according to the above mentioned statistics), recycling and reusing has never been more important than that of today.
The illustration shown below are of a linear system vs. a circular system. A key strategy towards moving into a circular economy is to use waste material as a resource (Huysman and De Schaepmeester et. al 2017). Therefore PET is used as a beyond end of life material with unlimited cycles of recyclability in the following example of a circular economy.

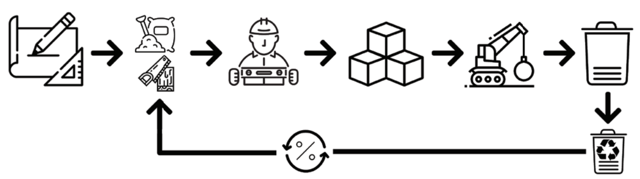


Image 1: Life cycle of traditionally built spaces Linear system with only a small percentage of demolished material is reused or recycled. (Own illustration)

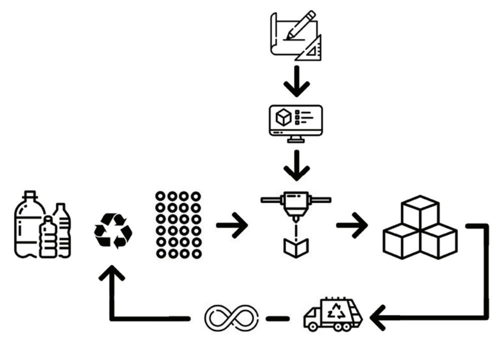


Image 2: Recycled PET based circular construction cycle (Own illustration)
Life cycle of Digitally manufactured spaces using recycled PET. Circular system where PET is a 'beyond end of life' material. Owning the base material with an infinite recyclability.

PET (SINGLE-USE WASTE)

Out of 8.3 billion metric tonnes of plastic ever made, 6.3 billion metric tonnes have had an unfortunate fate of becoming plastic waste (Parker 2018). With only 9% of the total waste being recycled, the majority 79% is accumulated in landfills or deposited in nature as litter (Parker 2018)

Therefore PET can be considered one of the largest sources of waste pollution due to its lack of proper disposal and sheer quantity of consumption. According to Eurostat, out of 246,130,000 tonnes of plastic waste generated in 2016, the Netherlands produces 8,393,719 tonnes of plastic waste comparable to Portugal producing merely half the amount (Eurostat 2019).

Often very cheap and easy to access, PET is a high-quality material used for very low-quality purposes, often as single-use objects. Posing a significant threat to the environment due to its non-biodegradability. It is estimated that 95% of the value of plastic packaging material is lost to the economy after a very short first-use cycle (Eurostat 2019). However, the material properties of PET in terms of durability should be considered a strength and incorporated for better use. With the potential to be recycled and reused indefinite times, recycled PET products have the potential to gain higher market value if used in the right context.

Recycled PET filaments are being made by companies such as Better future factory (Netherlands), Lancashire3D (UK) and Reflow (Amsterdam) to name a few. Therefore allowing for additive manufacturing methods to have easy and quick access to recycled PET filament to be incorporated in the manufacturing process. However, these products are mostly limited to small scale components rather than that of any significant scale of objects. This would reduce the materials full capabilities and potential.

RECYCLING PET WITHOUT DOWN-CYCLING

The most common method of recycling used for materials such as poly(ethylene terephthalate) PET, Polyethylene (PE) and polypropylene(PP) is mechanical recycling (Thiounn et.al 2019).

Image 3: Extreme example of plastic consumption

Image 4: Extreme example of living in consumed plastic waste

Thounn and Smith (2019) identifies and differentiates recycling into four main types for products such as PET;

1. Primary recycling; also known as closed-loop recycling. A method for taking the direct discarded plastics and directly turning it into a 'new' product with ideally no waste.(Al-Salem et. al 2009)

2. Secondary recycling; refers to mechanical recycling. The chemical identity of the polymer remains unchanged , but reprocessed, therefore used for different purposes than its original material. (Ignatyev, et.al 2014)

3. Tertiary recycling; sometimes referred to as chemical recycling. This process uses a chemical breakdown of the polymer into value-added commodities. Typical processes can be identified as hydrolysis (Al-Salem et. al 2009) and pyrolysis (Karthikeyan, et.al 2012)), then used as feedstock for production of fuels and polymers (Wong, et.al 2015)

4. Energy recovery; polymer is incarcerated and energy is recovered as heat.

However, different plastics have different pre treatments processes thus needing different methods of recycling (Thiounn et.al 2019). Contamination of plastic with general use can lead to unwanted chemical directions when being processed, these reactions can then alter the end result, decrease the efficiency of recycling method as well as change the properties of the end product. (Thiounn et.al 2019)

Given the urge to recycle plastic waste, many attempts have been made to commercialise recycling processes such as chemical recycling of PET having reached a mature state due to the relative ease of its depolymerization compared to other types of plastic (Thiounn et.al 2019). One such method, as patented by DEMETO is depolymerization by microwave technology, allowing for ten times faster reaction times of chemical processing. Industrial approaches differentiate between types of discarded waste, these can be categorised and looked into further detail as suggested by Thiounn et.al 2019;

- Industrial approaches to recycling mixed composition textile waste
- Industrial approached to recycling polyolefins
- Industrial approach to recycling mixed waste including SPI Code 3-7 plastic and other material
- Industrial advancements in mixed solid municipal waste.

Out of the above considerations, if needed to recycle PET without damaging the material properties or material strength, methods such as mechanical recycling can be used. Mechanical recycling is 'a method by which waste materials are recycled into "new" (secondary) raw materials without changing the basic structure of the material. It is also known as material recycling, material recovery or, related to plastics, back-to-plastics recycling'. (European Bioplastics, 2015). Below shows a depiction of the breaking down of PET as a material; allowing for the recycling process to substitute any elements lost in the recycling process to have an end product of the same quality as the initial product.

Conclusively, chemical recycling of plastics can be a convenient avenue to supplement the recycling process given the necessity to keep the value of PET unchanged. However, there may be more complex issues when it comes to the separation and purification of these plastics in real-world waste streams(Thiounn et.al 2019). Continuous efforts need to be made in the recycling industry to make chemical recycling more accessible, to consume less energy in the recycling process and also to scale recycling of plastic into an industrial level. Given the availability of recycling processes such as mechanical recycling (Thiounn et.al 2019), with an ability to produce a 'new' product using recycled PET with ideally no waste, in an ideal world there is definitely a possibility to

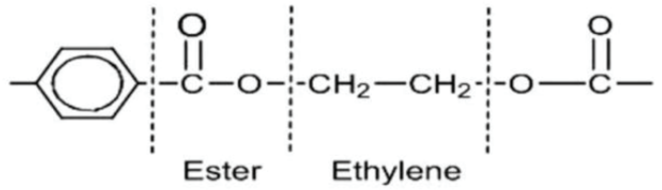


Image 5: Chemical properties of Polyethylene Terephthalate (PET) (Thomas et.al 2019)

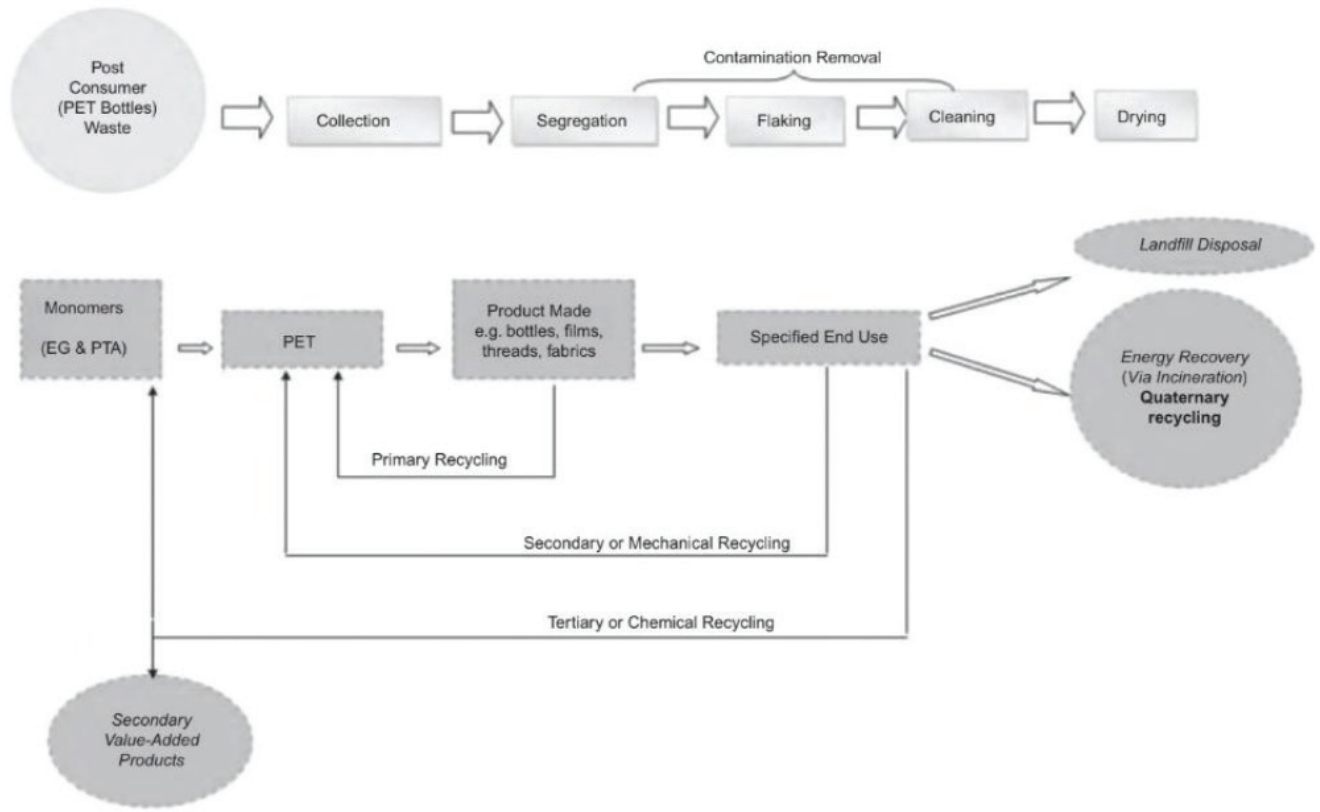


Image 6: PET recycling scheme (Thomas et.al 2019)

FUSED DEPOSITION MODELING
Fused deposition modeling (FDM) is an additive manufacturing technique (ASTM 2018). This digital manufacturing method divides a digital model into layers by a computational program and builds layer upon layer most commonly on X and Y coordinates (Labonnote et.al 2016). Due to the freedom of geometry, FDM allows for quick and inexpensive fabrication of models with complex shapes using a single material. The mono materiality allows for the produced object to very easily and simply be recycled and remade into printing filament as it is not contaminated or mixed with other material in the process of production.

INTERNAL LIVING MODULE
As an extreme example of cause and effect, the project will seek to design transformable multifunctional interiors for mono material FDM using recycled PET, prototype, validate and produce the final iteration, which then replicated, assembled into one adaptable tiny home (further detail explained in the Design task section of this report p.xx). Living in a structure made out of recycled PET would be an extreme statement made about the considerable amount of plastic consumed and discarded on a daily basis.
This project is to have a stronger impact and influence on the way we not only think about plastic but also as an eye-opener for the advancement in design technologies as solutions for the plastic waste problem.

All details will be aimed at being designed based on the possibility that they can be adapted into a different design based on the need of the user/ designer.

Out of the above topics only Additive manufacturing and Fused Deposition modeling will be further researched in the Literature review section page 20 onwards.

Image 3: 3D printed social housing, Mexico (NewStory) Fused deposition modeling

Image 4: 3d printed bathroom units (NTU)

2. RESEARCH OBJECTIVE

2.1 PROBLEM STATEMENT

MAIN PROBLEM

TRANSFORMABILITY OF MONO-MATERIAL PRINTED INTERIORS

To allow for recycled PET products to be of significance, higher market value and outlive its potential they need to be designed for improved purposes. For these adaptable interior surfaces to be adaptable, firstly should be designed ergonomically for each surface to serve single or multiple functions intuitive to an individual. Secondly for the surfaces to have multiple functions they need to be transformable. This transformability can be facilitated by movable parts that allow a single surface to transform, for different functional purposes.

SUB-PROBLEMS

1. DESIGN FOR MANUFACTURE AND ASSEMBLY (OPTIMIZING FOR MONO-MATERIAL PRINTING)

The entire design will be governed by constraints of the additive manufacturing methods used for prototyping; and the robotic arm used for the 1:1 scale model of the final design; Comau NJ602.2. Therefore effectively this design task having to adapt a design-build approach through its design phase.

The necessity to adapt a design-build approach is due to the end manufacturing method chosen for this project. With the designer having sole access to the FDM equipment, the designer needs to see through from design to optimization to the manufacturing of the product. It allows for changes to be made faster, easier and more efficiently due to the combination of roles assigned to the designer. Therefore designing for the manufacturing process and mode of assembly unique to the manufacturing process.

In order to obtain the maximum efficiency of the fused deposition modeling tools and the robotic arm (used for the final model), the transforming interior surfaces need to be optimized and tested according to print. To achieve a successful design the product needs to be optimized according to the print direction, efficiency of the print and the time taken for print. Spiralizing (printing in one run) as a method of Fused deposition modelling will be used to optimize the print. The design-build approach will allow for further changes to be made, during the printing process when necessary and proven needed due to results of prototypes.

2. RESEARCH BY PROTOTYPE

Prototyping is a commonly used method of exploring design and proofing of concept in design and architecture. Fused deposition modeling allows for rapid prototyping. Given that FDM is the manufacturing method used for the end product, prototyping using a similar machine and material will help explore and validate the manufacturing properties of FDM and the printing material (recycled PET). It is essential that a correct methodology is outlined from the start of the design to the end in order to have consistent validation of this project.

3. VALIDATION

Due to the minimal availability of design methodology to validate the specific topic of ‘Designing transformable multi-functional interiors for mono material FDM using recycled PET’, a new methodology for validation needs to be adapted according to the specifics of this design assignment. Proven methodologies from past product design guidelines and manufacturing guidelines will be reviewed in the Literature research section (p.28-p.35). In order to validate these design methodologies, sets of criteria need to be listed and weighted according to relative importance. (Further explained in detail p.12)

2.2 RESEARCH QUESTION

MAIN RESEARCH QUESTION

How to design multi-functional interiors based on transformable connections with mono material PET using Fused deposition modeling process?

SUB RESEARCH QUESTIONS

TRANSFORMABLE CONNECTIONS:

What transformable connections can be designed to extend the use of a surface and how can they be designed in order to allow for redesign and adaptability according to different needs of different users/designers?

What are the most optimal transformable connections that can allow for transformation according to specific functional needs of the different pieces of furniture?

What is the most suitable combination of transformable connections with surfaces for different functions?

VALIDATING RESULTS OF TESTING:

What methodologies can be used to most accurately validate the results of prototyping and testing according to the different criteria set per design component?

DESIGN FOR MANUFACTURING AND ASSEMBLY:

What effect does FDM process have on the design process

What impact does making the designs, methodology and system available to the masses though the maker movement?

PROTOTYPING:

To what extent can prototyping be incorporated into the research-by-design process and how can it be most effectively used for testing transformability of interior furniture?

How is the design output affected by the prototyping process and machine limitations? Can they be used as strengths when designing?

2.3 DESIGN TASK

With the aim of giving recycled PET an improved purpose, the material will be digitally designed interior components and rationalized for the additive manufacturing process. As an extreme example of the possibilities of FDM using recycled PET, a single module of a modular tiny home focusing on a modular customizable system of interior components will be designed in a few design tools (further explained in the Methodology section). A standardized flexible connection system, optimized and tested for FDM will be designed and shown by exemplary iteration of interior modules. The standardized transformable connection system allows design freedom for who ever incorporates a modular component system for any project here onwards. The standardized transformable connection system hopes to take advantage of the open source nature of FDM prototypes readily available on many on-line platforms like thingverse.com to allow a designer to adapt these tested transformable connections into their design.

The design task will be carried on and validated using the following steps (more detailed descriptions provided in the Methodology section);

1. Literature research
2. Research by design (Using prototyping as proof of concept)
3. Validation matrix using prototyping (Designing, prototyping, Testing, Validating and iterating)
4. The final transformable connections chosen and combined together into one exemplary design.

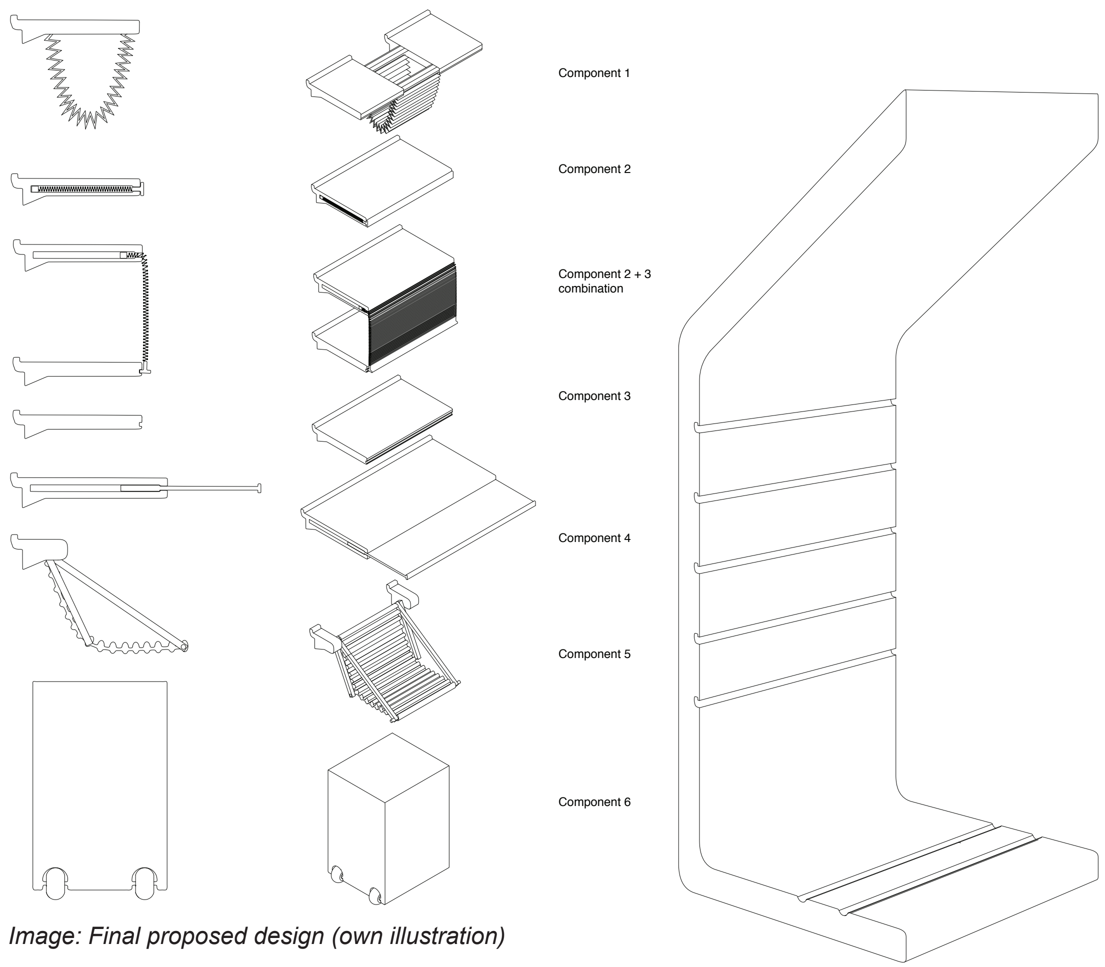


Image: Final proposed design (own illustration)

2.4 RELEVANCE

RELEVANCE FOR BUILDING TECHNOLOGIES TRACK

Building Technologies stemming from the field of Architecture branches out into many different pathways. Having been taught and introduced to many different forms of architectural expression, Additive manufacturing could be identified as one of the fastest growing manufacturing processes in experimental architecture. Due to advancements in technologies and its easy availability additive manufacturing is used in almost every branch of building technologies; Climatic design, Facade design, Structural design and sustainable design. Building technology from the start had a strong drive towards normalizing sustainability measures when diving into any design project. The normalization of sustainability and increasing incorporation of additive manufacturing in architecture and design drives this project to its maximum potential. Using recycled PET as a sustainable building material and additive manufacturing as the primary method of manufacture heroes this thesis as a good example of how building technology progresses beyond conventional architectural design and construction methods.

RELEVANCE FOR MSC AUBS

Architecture is a field adapting to the developments of technology fast. Conventional design and construction methods for architectural designs are being questioned and rethought in a time where sustainability and a circular economy has become crucial for the sustenance of this planet. Architecture as a field of study should embrace new methods and technologies to promote new ways of thinking, designing and manufacturing as all great architects of their times have done. Additive manufacturing methods allow for unique and complex designs to be manufactured where conventional manufacturing methods fail. Further the topic of sustainability has been a long standing drive for teaching architecture in the faculty of TuDelft, therefore I believe this thesis topic would be an exemplary subject of how architecture is progressing and should be approached by the creative mind.

SOCIAL AND PROFESSIONAL RELEVANCE

As made evidently clear in the start of this graduation report, there is a consistent urge for society as well as for professionals in the field of architecture to be more aware of the impact of what they design and produce has on the environment we live in. It has never been more important than now to be sustainable, be more circular and be aware to cut down on negative impacts individuals and the professional workforce imposes on the environment. Out of 8.3 billion metric tonnes of plastic ever made, 6.3 billion metric tonnes have a sad fate of becoming plastic waste. With only 9% of the total waste being recycled, the majority 79% is accumulated in landfills or deposited in nature as litter (Parker 2018) it is our responsibility as a society and as the workforce to strive for solutions. As an extreme example, this thesis will have an outcome of a 1:1 module of the interiors of a tiny house entirely printed out of recycled PET using additive manufacturing. Intended to be a statement for the staggering amount of plastic waste produced and discarded improperly, this thesis strives to set an example in the professional field of architecture to use resources wisely and efficiently. The use of Additive manufacturing further explores the robotics as a manufacturing method sparsely used but swiftly becoming easily available, popular and widely used for experimentation not only in the field of architecture but many other essential fields of study.

SCIENTIFIC RELEVANCE

The most dominant relevance of this thesis to the scientific framework is the methodology. Due to the limitations of available scientifically proven methodologies available for Designing transformable multi-functional interiors for mono material FDM using recycled PET, a new methodology needed to be formed. Existing methodologies aimed at a similar design process were taken into consideration, adapted and readjusted to fit the specific needs of this design assignment. Once the methodology is validated using prototyping and testing, it can be used for impending projects of a similar design sequence.

3. DESIGN TOOLS: LITERATURE RESEARCH

INTRODUCTION

The literature (theories or research data) and general practical experience/precedent you intend to consult.

A selection of topics for “Background research” was conducted in order to validate the purpose of this design assignment. Research was conducted on topics such as; Current situation (Environmental situation, Need for more sustainable solutions as architects as designers, social responsibility in the field of design), 3D printing, Fused deposition modeling. The above information allows the justification of the design task on a larger scale with dominant social and environmental implications. Further research on Design research methods, product design theory and methodology, Designing for manufacturing techniques, design methodologies, prototyping and Ergonomics and anthropometric measurements studies were conducted. (Detailed information to be presented with the report

Scientific papers, previous master thesis, related publications, websites and information from liable educational institutions who have realized projects of a similar topic will be used as sources to form a just argument for this thesis.

Statistics dating back to maximum 8 years will be used. Theoretical information with regards to methodology etc. will not have a time frame depending on its relevance to the current times and methods.

3.1 MANUFACTURING PROCESS (ADDITIVE MANUFACTURING)

Yang et.al describes Additive manufacturing (AM) as a process that evolves with the design from the initial rapid prototyping to the end-of-use product manufacturing process. Due to the necessary integration of all steps from start to End-of-life (EOL), AM is a process that requires complete transparency in changes at all times with its ‘shape, material, hierarchical and functional complexities’ (Yang et. al 2015 p.327). These four complexities completely co-dependant of one another, gives AM the competitive advantage of design freedom over conventional subtractive or formative methods of manufacturing (Yang et.al 2015).

According to the American Society for Testing and Materials (ASTM) 52910 Standards, Additive manufacturing processes can be divided into 7 categories according to standard terminology for additive manufacturing technologies. The seven processes are as follows (ASTM 2018):

1_ Vat Photopolymerisation
- a_ Stereolithography (SLA)
- b_ Digital Light Processing (DLP)
- c_ Continuous Liquid Interface Production (cLIP)

2_ Material Jetting

3_ Binder Jetting

4_ Material Extrusion
- a_ Fused Deposition Modeling (FDM)
- b_ Fused Filament Fabrication (FFF)

5_Powder Bed Fusion
- a_ Multi Jet Fusion (MJF)
- b_ Selective Laser Sintering (SLS)
- c_ Direct Metal Laser Sintering (DMLS)

6_ Sheet Lamination

Additive manufacturing can be used in different mediums. A few identified by Ratto are, fashioning custom tools to accomplish different tasks, extending or connecting disparate forms, systems or structures, visualizing problems that are difficult to picture virtually, allow for individual expression of aesthetic taste and individualism (Ratto, 2012). The variety of production possibilities make AM a strong contender for producing computationally designed complex geometries.

Out of the above 7 additive manufacturing techniques categorised by ASTM, Fused deposition modeling (FDM) will be proposed for this design assignment. Due to the requirements and machinability of the Comau NJ602.2 robot arm, the design will be adapted accordingly.

FUSED DEPOSITION MODELING (FDM)

FDM is an extensively used additive manufacturing process for fabricating prototypes and other components using common engineering plastics. Based on extruding heated plastic filaments or pellets through a nozzle tip to deposit layer upon layer directly extracted from the digital model (Masood, 2004). FDM is simple, reliable and relatively inexpensive, making it widely recognized and used by industry, academia and individual consumers (Masood, 2004).
'The principle behind the majority of the additive processes including the 3D printing, involves layarization: slicing digital models into horizontal layers and building the object up one layer at a time' (Ratto,2012). Commonly used extrusion head uses temperature controlled thermoplastic polymer filaments that move in X and Y axes while the platform on which the model is to be built lowers in the Z direction. The layer deposition can be controlled, but is usually ultra thin (Katti, Sharma et.al. 2017). Due to the relative simplicity of this manufacturing method, when clearly understood and put into practice, FDM allows for great design freedom of form and efficiency.

The design freedom stems from the designer having hands on control over the entire process from design to manufacture. The ability to control and operate additive manufacturing machines such as the Comau NJ602.2 robot arm by the designer itself, eliminates all discrepancies within the different parties involved in the realization of a traditional production system post design.

However, to be critical, conventional FDM does have its limitations in material availability, limitations for geometry such as minimum thickness and reach of the device, dimensional accuracy, unevenness of the surface and also the effect external environments have in the drying/curing process (Yang et.al 2015). These clauses are to be considered and implemented when optimising the design according to FDM.

FDM AND DESIGN-BUILD APPROACH

Since the 1960s, computers have been used as a support tool for rapid prototyping and aid for manufacturing using FDM in large industries (Ratto, 2012). Due to the easy availability of digital aid for designing and manufacturing, any individual with access to FDM machinery connected to a computer has the ability to become their own manufacturer. Although access to real-time printers may not be as common, individuals do have easy access to software that develops 3D printing products, allowing for direct engagement in the design process and the act of making itself. (Ratto,2012)

Conventional design theory and methodology (DTM) has been significantly limited by manufacturing technologies of mass production due to 'iterative compromises in functionalities and performance (Yang et.al, 2015). The possibility to apply functionally complex applications to manufactured purely because AM is being used, the easier it is to generate solutions to the design problem at hand. "Alongside notable shifts in consumer behaviour… In the contemporary digital economy, consumers increasingly seek out individualized experiences and expect that products be tailored to their specific needs, wants, contexts and tastes." (Ratto 2012). Because the design-build approach allows for quick and easy impositions by the designer at any moment of the production process, if needed, changes in customization can be implemented without haste. Further, if an object is to be printed multiple times and requires smaller changes for customisation, this too can easily be achieved by the designer for FDM at the source of the design (a computationally designed file).

ADDITIVE CONSTRUCTION

Traditional construction methods entailing physical labour has shown to stagnate or decline due to it being labour intensive and the lack of interest shown by each new generation in qualifications/ education necessary to be apart of the building industry. (Labonnote et.al 2016) in contrast to this, FDM in the past decade facilitated for shorter design and development cycles and cheaper manufacturing costs all while increasing communication and collaboration between designers and engineers because of it being open source (Labonnote et.al. 2016).

FDM in additive construction is defined as a compilation of the entire process of building a digital form (building design) using material interpolated on-site (material science) according to a digital model sliced for printing optimization (engineering) (Labonnote et. al 2016). When implemented correctly, AM has the capability to revolutionize the work process, change the relationship between the designer, every party involved in between and the manufacturer by unifying the entire production process due to the ease of operation as explained in the FDM and design-build approach section above.

Rapid manufacturing methods as competitive substitutes for construction of housing and other large scale products have the potential to revolutionise the construction industry in its entirety if three challenges are tackled by architects and designers. The 'need for an architectural paradigm shift, the need for a holistic design approach and the need for rational designers' identified by Labonnote et.al in her research (Labonnote et. al 2016). Approaching an age of normalizing AM methods, it is important as architects and designers that we incorporate these manufacturing methods for its full potential, by exploiting all possibilities to make architecture and design more sustainable and responsible.

Additive construction 'process of joining materials to create construction from 3D model data, meaning the design, production and/or assembly will be digitally controlled at least to some extent, with the ease of making fast, small changes to the design while in the printing process. This is possible because additive manufacturing; the 'Process of joining materials to make objects from 3D model data' is based on a 'layer upon layer' approach as opposed to subtractive manufacturing methodologies (CNC milling) (Labonnote et.al 2016). The layering process gives competitive advantages to FDM by allowing for quick iterations throughout the design process when deemed necessary, according to sudden changes in the construction environment, traditional construction methods can't instantly adapt to.

Comparative to all the advantages of incorporating additive manufacturing methods into the large scale construction industry, Labonnote et.al. points out a valid statement true to the current time that additive manufacturing will only integrate itself as much as the more traditional methods of manufacturing has, if 'housing (or other constructions) in general changes to become more optimised and more individualised' (Labonnote et. al 2016). Ratto interprets Von Hippels's (2005) idea of customization as having a gap between the users' heterogeneous needs for a certain product or technology and adequate satisfaction provided to the consumers by mass production. Ratto then points out that the solution provided to this problem in the mass production dominated market is 'specialized elitist items' given to the consumer by means of different options in a later production phase. (Ratto 2012)

Additive manufacturing processes are based on the deposition of a material in a viscous liquid form via a printing nozzle. Thus referred to as 'extrusion-based process'. It is possible to solidify the material, achieved by curing the following extrusions. Therefore it is possible to choose any material from the following material families to be used for FDM

Bulk material used for FDM may include; (Labonnote et.al, 2016)

1. Natural aggregates (such as soil, sand, natural gravel, crushed stone, clay or mud),

Number of axes	6
Maximum wrist payload (Kg)	60
Additional load on forearm (Kg)	20
Maximum horizontal reach (mm)	2258
Torque on axis 4 (Nm)	221
Torque on axis 5 (Nm)	221
Torque on axis 6 (Nm)	118
Stroke (Speed) on Axis 1	+/- 180° (170°/s)
Stroke (Speed) on Axis 2	-60° / +125° (150°/s)
Stroke (Speed) on Axis 3	0° / -165° (165°/s)
Stroke (Speed) on Axis 4	+/- 2700° (265°/s)
Stroke (Speed) on Axis 5	+/- 123° (250°/s)
Stroke (Speed) on Axis 6	+/- 2700° (340°/s)
Repeatability (mm)	0.06
Tool coupling flange	ISO 9409 - 1 - A100
Robot weight (Kg)	645
Protection class	IP65 / IP67
Mounting position	Floor / Ceiling / Sloping (max 45°)
Operating Areas A (mm)	2408
Operating Areas B (mm)	2258
Operating Areas C (mm)	1918
Operating Areas D (mm)	686
Operating Areas E (mm)	941

Image: ComauNJ602.2 aRobotic arm specifications (Comau.com)

2. Recycled aggregates (such as those from construction, demolition, or excavated waste),
3. Manufactured aggregates (such as air cooled blast
4. Furnace slag and bottom ash) or natural fibers (such as cellulose and recycled wood fiber

Bulk materials need to be combined with binding pastes as; (Labonnote et.al, 2016)

1. Cement consisting of mixtures of oxides of calcium, silicone and aluminum
2. Polymer blend

When considering to print for construction, it is important to consider the following extrusion-based process-related characteristics (Labonnote et.al, 2016);

1. Pumpability: ease and reliability with which the material is moved through the delivery system
2. Printability (extrudability) ease and reliability of depositing material through a deposition device
3. Buildability: resistance of deposited wet material to deformation under loads. (number of filament layers that can be added on top of each other before deforming the lower layers
4. Open time: period during which the aforementioned properties remain consistently within acceptable tolerances

COMAU NJ602.2

The following specifications are of the robot arm that will be used in the final print of the 1:1 prototype. The reach, rotational axis and print speed are a few advantages to using this machine.

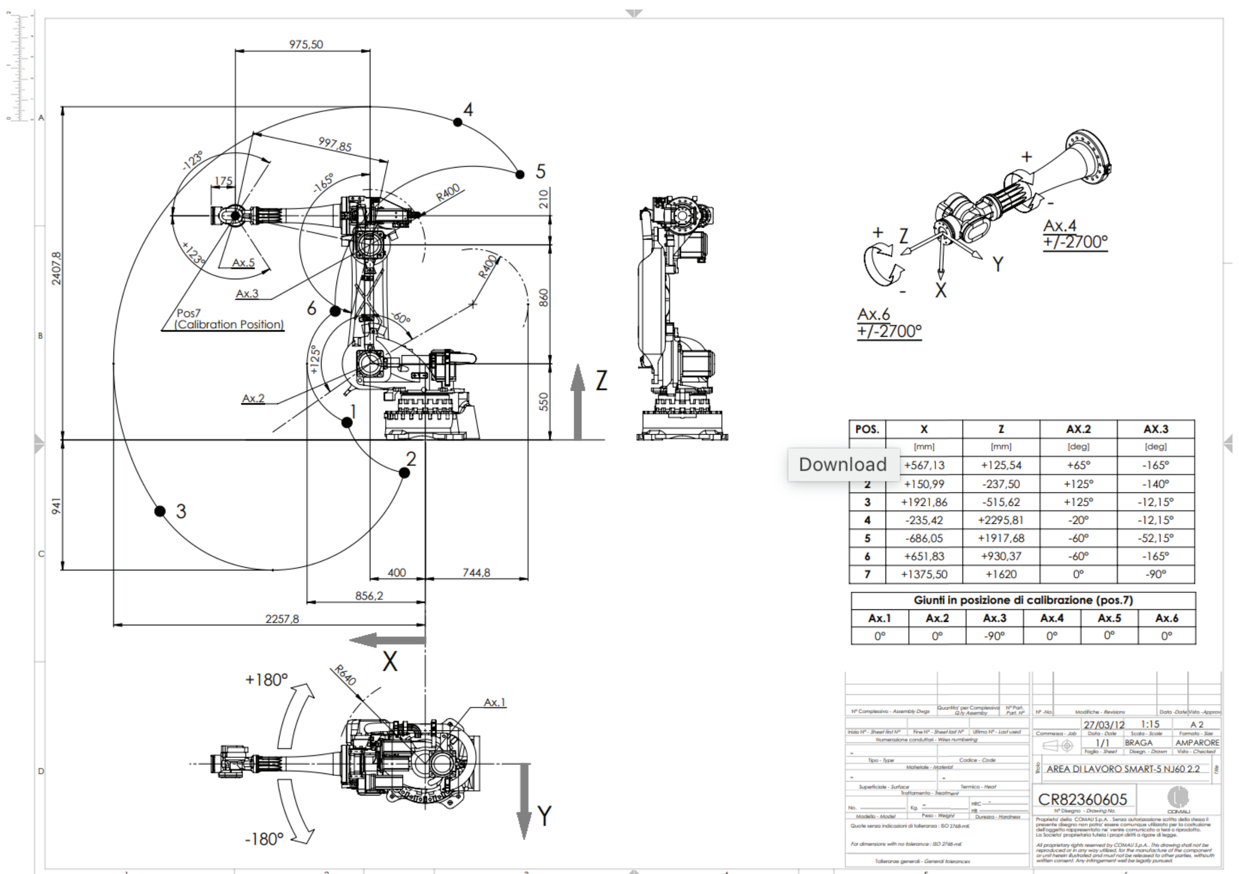


Image: dimensions for Comau NJ60 2.2 robotic arm (Comau.com)

ADDITIVE MANUFACTURING VS. TRADITIONAL MANUFACTURING

The following comparison is purely based on this specific project and is relevant mainly and specifically to this project based on Customizable components for additive manufacturing and other methods of manufacturing catering to the requirements of this design project.

Given the nature of this project, a few considerations were taken into account when choosing and settling for additive manufacturing as the main manufacturing process. These considerations are as follows;

Design components are to be customized by the designer rather than having a single design to be mass produced. This may be called mass customization.
The design components are to be made available on maker platforms Online for anyone to access, download, customize, and print (possibly in the comfort of their own home). Recycled PET to be used as the main manufacturing material. Therefore a strong urge to use a manufacturing method that can allow for using recycled PET needs to be chosen.

Given the special considerations specific to this design task; the following comparison was conducted between traditionally existing methods and additive manufacturing. The below information is a summarized version of the articles written by Nadin 2016 and Pereira et.al 2019.

Contrary to traditional manufacturing methods such as Subtractive manufacturing and formative manufacturing where the material is removed via machining, drilling, grinding or cast into moulds, additive manufacturing allows for a higher level of design freedom given the layering system (Connor et.al ,2014). However, standardization and established Design For Additive Manufacturing is still in a progressive stage and requires more work in order to be competitive against traditional manufacturing methods considering competitive pricing for larger quantities and speed of production (Pereira et.al 2019).

ADDITIVE MANUFACTURING	TRADITIONAL MANUFACTURING METHODS (I.E INJECTION MOLDING)
- Cost of production remains the same for one piece or a 100 pieces. With this method, smaller businesses and individuals without access to large scale manufacturing methods can still design and produce their own products. - Due to the COP remaining the same for manufacturing the only variable factors being time and material, allows each piece to be customized as required. Reduces lead times for short production runs and allows for manufacturing of complex shapes without added costs in terms of material, man power and manufacturing specializations. - Additive manufacturing is an additive process which means the end result may vary according to external influences/ machine differentiations because of the individualization of access to printers by people from around the world. However, smoothing techniques are being brought forwards by companies such as Sculpted to reduce discrepancies in the printing process. - Size of production is limited given the restrictions in the size of the pruning bed. However, production resources such as robotic arms have made printing on a large scale possible. Example: comau NJ2 602.2 available in the LAMA lab of TuDelft faculty of architecture having a printing reach of more than 2m in height and 2m in length. - Efficient material usage, as there are no extra material discarded in the printing process	- Mass production means the more quantities ordered for production, the cost decreases. Therefore producing one off objects will cost substantially more compared to larger quantities. However. Pricing is competitive when producing large quantities of the same object. - Injection molding and other traditional manufacturing techniques provide a larger variety of testes and proven materials to select from. However for the case of this project, 3D printing has efficient use of recycled PET as a manufacturing material. - Molding and plastic forming allow for smooth, perfect finishes and less room for error based on the repetitive technique. - Manufacturing on a large scale is possible.

Table: Additive manufacturing vs. traditional manufacturing summarized

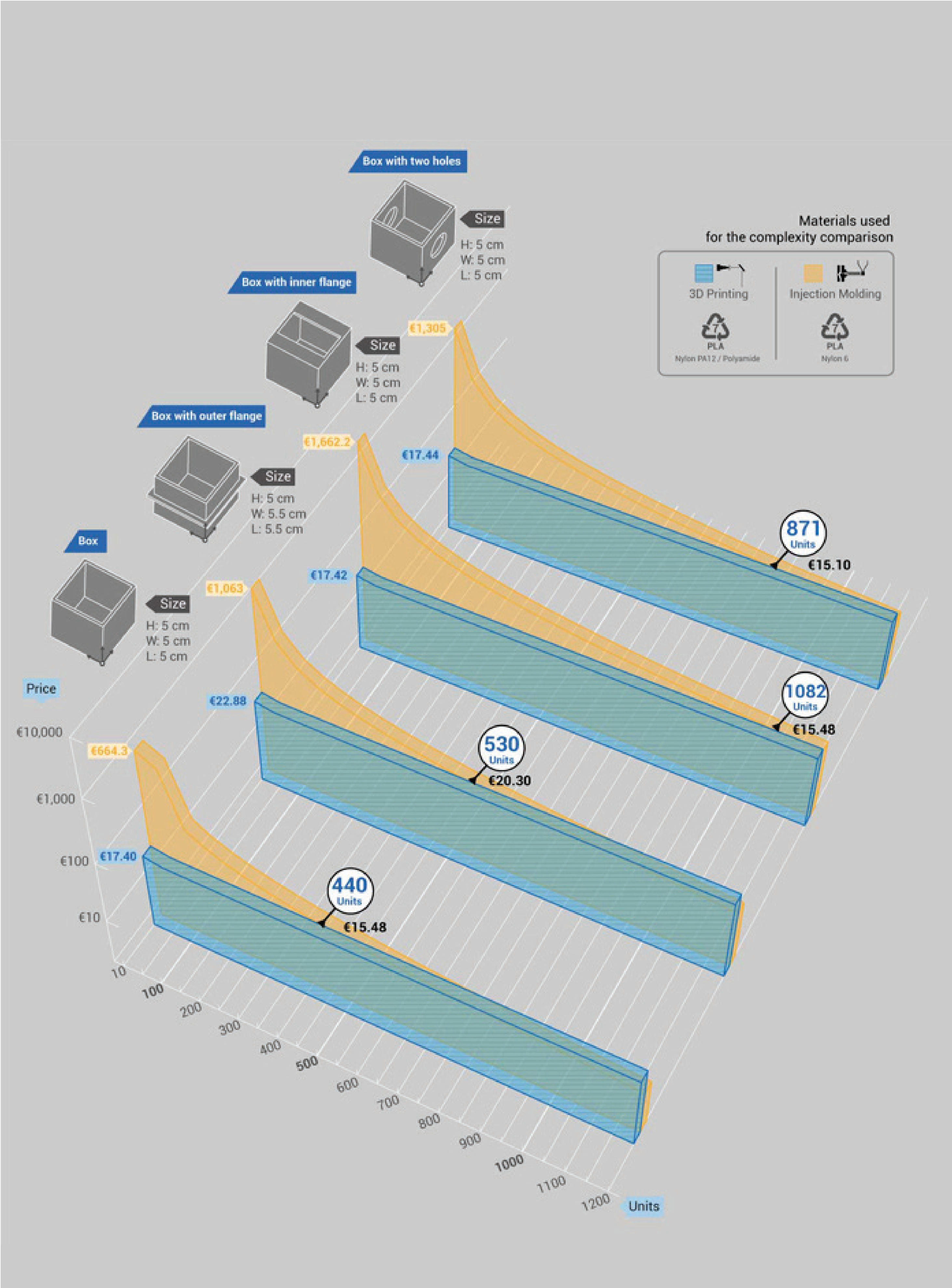


Image: Influence of complexity On the graph, you can see that the more complex the box is, the more expensive it gets to produce with injection molding. Sculpteo.com

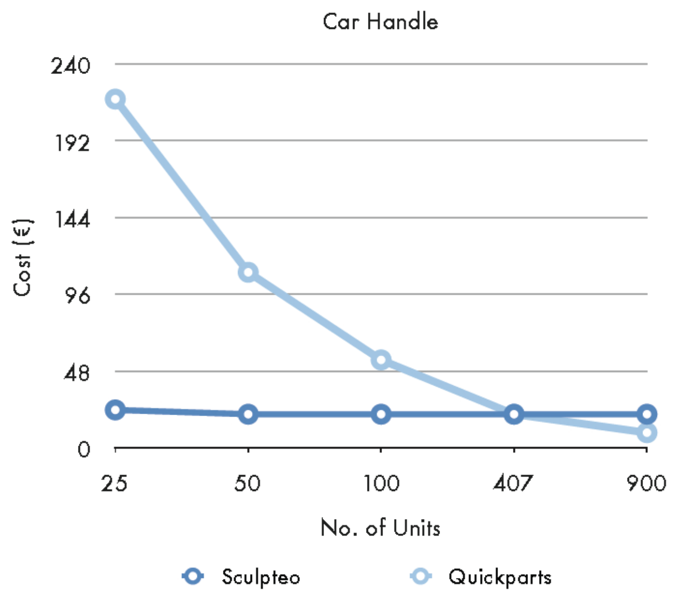


Image: study done by Sculpteo showing the comparative price of a car handle produced by injection moulding (Quick-parts) or additive manufacturing. Upto 407 units, it remains cheaper to use 3D printing. Sculpteo.com

Given the specific nature of this project and the need for mass customization, public availability for the maker movement and specified use of the material, comparative to traditional manufacturing methods such as extrusion moulding, Additive manufacturing outweighed its advantages for this specific case. With only time and material as variables affecting the manufacturing process, the cost of production remaining the same, additive manufacturing allows for mass customization may it be one object or multiple objects to be manufactured. The flexibility of additive manufacturing as the core manufacturing method for this project is therefore justified based off criteria for this specific project.

CASE STUDY 1: 3D PRINTED NEIGHBORHOOD NEWSTORIES

Example: 3D printed neighborhood by New Story
A 33 foot long 3D printer is used to print the world's first 3D printed neighborhood. Each house designed to be 500square-feet, finished with roofs, windows and interiors attempts to be a solution for affordable housing in some of the poorest communities in the world. Having built 2,700 homes using traditional construction techniques in Haiti, El Salvador, Bolivia and Mexico, it was recognized that constructing these homes using additive manufacturing techniques can reduce costs and speed up construction time (Peters 2019). Partnering with Icon, a construction tech company, NewStories developed their own 3D printer called Vulcan II with the ability to work in almost every possible condition (Peters 2019). Having to build in earthquake prone areas such as Tabasco bordering Guatemala, the design was further structurally optimized to withstand such conditions (Peters 2019).

A software that monitors the weather outside internally adjusts the concrete mixture before extrusion, allowing for customized viscosity according to external weather and consistent print quality throughout the day (Peters 2019). A total of 24 hours over multiple days consumed to produce two homes, with parts that were not 3D printed, produced by local workers providing jobs (Peters 2019). This project further justifies the possibility that additive manufactured homes can solve the excessive price tag on housing. For proof, Icon suggests a 3D printing revolution in the construction industry as a solution to the growing housing crisis due to three critical problems (Iconbuild.com);

1. **Affordability:** An average person cannot afford a home
2. **Sustainability:** Homebuilding is inefficient and wasteful
3. **Availability :** Over 1 Billion people do not have adequate shelter.

Icon build uses their own 3D printer Vulcan II with the following specifications using Icon's very own proprietary Portland Cement-based mix.

Image: Falcon II printer on site (Joshua Perez/ Courtesy New story)

Image:3D printed home (Joshua Perez/ Courtesy New story)

Image:3D printed neighborhood (Joshua Perez/ Courtesy New story)

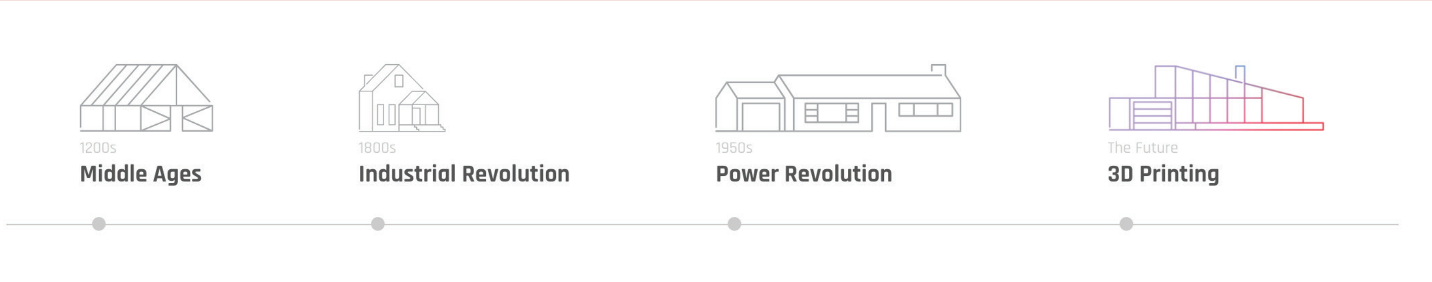


Image: Revolutions in the construction industry (IconBuild.com)

CASE STUDIES FOR ADDITIVE MANUFACTURED PROJECTS OF RELEVANCE

CASE STUDY 2: 3D PRINTED BATHROOM NTU

Example: 3d printed bathroom time efficiency
The 3D printed bathroom unit by Nanyang Technology University of Singapore sets an example with their 3D printed bathroom units using concrete, suggested to be printed in 9-12 hours (Lavars 2019). Material and weight savings upto 30% with half the construction time of regular prefabricated bathroom units of the same size (Lavars 2019). Therefore 30% quicker to build and 30% lighter with material usage. Singapore sets an example as a country to set regulations for promoting additive manufacturing methods by requiring certain types of large scale projects to be built off-site in order to save manpower and time, in order for workers to be redeployed for higher-level specialised tasks (Lavars 2019).

Although having used eco friendly geo polymers and fly ash waste, a downside of this project would be that interior fittings such as tiling, fixtures, mirrors, drainage systems etc were commonly used industry standard non renewable fixtures that took an estimated 5 days to be fixed on (Lavars 2019).Although the exterior walls and structure were 3d printed, Is it really feasible and environmentally friendly due to all the added material to make this module functional?

Image: (From left) Mr Lie Liong Tjen from Sembcorp Design and Construction, and Sembcorp Architects & Engineers, with Nanyang Technological University's Associate Professor Tan Ming Jen and Associate Professor Wong Teck Neng.ST PHOTO: KEVIN LIM strait times

Image: How a bathroom is printed (NTU, Graphics: Straits times p.B6, 24th May 2019)

SUMMARY

Fused deposition modeling (FDM) stems from 7 other possible Additive manufacturing (AM) methods as categorized by the American Society of Testing and Materials. FDM is based on a layerized extrusion process. The variety of production possibilities gives AM a competitive advantage over other traditional production methods for producing complex geometries. The manufacturing process facilitates design freedom in form and geometry, allows for the designer to be in control of the entire process from design to manufacture and eliminates discrepancies between third parties involved in the external manufacturing process and the need for third party services at all.

AM has the ability to change the relationship between designer and every other party involved in the process of designing for production by unifying the entire production process due to ease of operation. This could be identified as a design-build approach for AM. Due to the disparities, increased costs and increased time frame of production of traditional construction methods, as architects and designers, it is important to adapt fast, cheaper and more efficient manufacturing methods such as FDM for their designs.

Comanu NJ602.2 robotic arm will be used to produce the final 1:1 prototype once designed.

Realized projects such as the world's first 3D printed neighborhood in Mexico by New Story and an experimentational prefab 3D printed bathroom by Nanyang Technology University of Singapore are pioneering the normalization and implementation of FDM for everyday use in human scale designs.
However, the only drawback being that although 3D Printed, the above mentioned projects still use many other materials in its final design to allow for functional necessities. Therefore still depending on

3.3 DESIGN RESEARCH

Due to the minimal availability of specific scientific information regarding the thesis topic; ‘ Designing transformable multifunctional interiors for mono-material FDM using recycled PET’, other existing literary sources with design research methods were deliberated and repurposed. Product design research methods were researched for their existing methods and scientific testing for validation processes. It was therefore, possible to identify a single or multiple connections within existing research.

The design task was broken down into stages so that each stage could be defined more efficiently. In order to reflect freely on a certain design task at hand and to avoid making premature decisions based on the lack of knowledge hitherto, Bonsiepe suggests ‘a fluid physical state (of thinking) is preferable to a solid one’. (Bonsiepe, 2007 page 27) Fluid states that are “free from all the calculating attitudes associated with need and use.” (Gadamer,1991). With certain criteria predetermined according to the basic necessities of the design assignment, it is important to identify justified methods of design research to validate findings according to the design task.

Bonsiepe interprets Bruce Archer’s in 1981 characterization of design research as a form of ‘systematic inquiry performed with the goal of gathering knowledge in the form/embodiment of- or in- design, composition, structure, purpose, value, and meaning of human-made things and systems’ with a conclusion that ‘design research is a systematic search for the acquisition (performed with the goal of gathering knowledge in the form/embodiment) of knowledge related to design and design activity (composition, structure, purpose, value, and meaning of human-made things and systems)’(Bonsiepe, 2007 p.28). He further expresses that ‘The designer observes the world with an eye to its designability, unlike the scientist who regards it from the perspective of cognition’ (Bonsiepe, 2007 p.28), comparing cognitive design versus non-cognitive design. Therefore needing different design research methods for design specifically, comparable to those in the field of scientific research. Once provided of these research methods, Bonsiepe encourages to consider the importance of reflecting on research; to take a step back from the work and to thematize all interdependencies and discrepancies as a necessary step in design research ((Bonsiepe, 2007 p.28). Reflecting on these methods will facilitate for a more intricate definition of chosen methodologies.

Bonsiepe points out a very valid argument that “If… designers can no longer design the way they did one or two generations ago, then it also must be acknowledged that researchers can no longer do research as they did one or two generations ago- i.e orientating themselves primarily or exclusively by texts.” (Bonsiepe, 2007 page 37). Indicating there is no restriction in combining research methods due to the availability of extensive types of resources and processes. In a time where technologies in architecture and design are changing so rapidly, adapting research methods may it be text or physical testing, interdisciplinarily when suited, with justifiable validation clauses should be considered a more viable solution for research in current times. Design research as a field of scientific research continues to grow minimally through industrial design and other fields of design but thrives in the field of engineering because of the necessity to numerically validate tests, although limited results of practical application and validation can be seen to be relevant for design research purposes (Cross, 2001).
One such design research commonly used in Industrial design and slowly emerging in Architectural academic research is Research through design (RTD). Providing the epistemological concepts for the development of a genuine design research paradigm where no foundations comparable to those in science are available, providing a con
dition for methodological development (Wolfgang 2007).

RESEARCH IN PRODUCT DESIGN

The previous design research reviews are based on literary writing in the field of product design. With intentions of the product to succeed by its design, specifications need to be set out from the start of the design process for clarity. Product design specifications as defined by Morris are a collaboration of summarized thoughts, research, imagination and data put together in order to define the proposal and conceptual brief in a more detailed manner. It allows for the complete product to be defined and to explore work that is set out as criteria but also other tasks that needs to be done in the future (Morris 2009, p.54)

A particular way of brainstorming design suggested by Morris is Analogy comparisons. An analogy drawing on another analogy allows for a comparison between two different objects unrelated to each other as an example, an airplane as analogous to a bird, both adapting similar solutions to achieve one function, flight. ‘This problem makes me think of X (analogy)- that suggests that maybe we could try Y (Idea drawn out from analogy X)’ (Morris 2009). The analogies can be natural, personal, remote or fantastical (Morris,2009). Analogy comparisons can also lead to thinking through principles rather than to be marginally influenced by existing solutions according to specific functions.

It is important to keep the end user perception of the product in mind when researching and testing for product design. Methodologies such as The House Of Quality (further explained in Design for Manufacturing (p.31) facilitates all members involved in a product design to be aware of how each different speciality is affected by changes made in others, and to act accordingly to adjust necessary factors for customer perception. A product that uses slower methods, more materials, or takes longer to assemble by just slightly more than its rivals is already at a major competitive disadvantage no matter how well it has been designed (Morris, 2009, p.127).

SUMMARY

Due to the lack of specified design research methodologies, methods were to be adapted by existing methodologies for design research from the fields of industrial and product design. It is important to keep in mind of the perception of the end user and the designability while maintaining a fluid state of mind. Since designers cannot design as back in the day, researchers shouldn’t be able to research using the same old methods from years before either. Blurring the line between what should be acceptable as a methodology for design research. Design research as an academic field of research continues to grow slowly and needs validated methodologies to justify certain choices. Prototyping and using methodologies such as The House of Quality can allow for validating design research.

3.4 DESIGN FOR MANUFACTURING

DESIGN CONSTRAINTS FOR MANUFACTURING

In opposition to subtractive and formative processes, the layer-by-layer mechanism directed by CAD software allows for virtually any shape or form to be manufactured according to the designers imagination (Yang et.al 2015 p.329). Therefore once the designer has substantial knowledge of the manufacturing requirements and material used for production, the need for a third party manufacturer is eliminated, giving sole control over the entire design and manufacturing process to the designer itself. Therefore designed to manufacture.

“The research indicates that the traditional part complexity measurement that is based on cost of manufacturing, cost of assembly and serviceability are challenged by additive manufacturing due to the fact that the way of calculating manufacturing cost and assembly has totally changed.” (Yang et.al 2015 p.329). Since the cost of production excludes payments made to third party individuals controlling a complicated manufacturing process, a significant decrease in cost of production can be seen. To further optimist a design according to machinability, Yang et.al groups guidelines for conventional Design for X in a formatted language as below (Yang et.al 2015 p.331) ;

1. Design simply: simplify structures complying with functional requirements;
2. Minimize part count
3. Integrate parts.
4. Separate working components into modular sub assemblies.
5. Minimize material types in assembly.
6. Standardize components.
7. Create multi-functional parts.
8. Design for ease of fabrication.
9. Design for ease of assembly: positioning, handling, joining and access.
10. Avoid using laminates.
11. Avoid surface demands on components.
12. Avoid secondary operations.
13. Eliminate adjustments.
14. Use ferromagnetic materials.

The entire design process will be driven by its manufacturing process. Due to the nature of FDM and the manufacturing controls, several changes and optimizations are allowed to be made throughout the design and manufacturing process. ‘To optimize the parts of the product with respect to the assembly and manufacturing, DFM and DFA can be performed directly in the design without generating additional constraints or changes in the initial request of the end user’ (Boyard; Rivette et.al 2013)

The properties of the material and output of the material quality due to the printing process needs to be taken into serious consideration, and can be tested through

rapid prototyping as a design validation tool. It is important to be governed by design guidelines and methodologies for Design for Manufacture and Assembly (DFMA). These methods then need to be adapted and incorporated in a complementary way to the methodology of this design task(Living in a bottle) learning from other realized and research projects for the best possible design-build approach.

3.5 DESIGN METHODOLOGIES

AM RELATED DESIGN METHODS/GENERAL DESIGN GUIDELINES FOR AM

Due to the lack of specified design methodologies for the specific topic of ‘Designing transformable multi-functional interiors for mono-material FDM using recycled PET’ a new compilation for a justifiable methodology was to be found. The following research into existing methodologies allowed for identifying suitable concepts for different parts of the methodology that was created specific to this project.

Becker et. al explores some design guidelines for additive manufacturing. With reduced part count, less assembly effort and advanced functionality a few clauses to consider when defining a design methodology by Becker et.al interpreted by Yang et.al are as follows;

1. Use the advantages included in RM processes.
2. Do not build the same parts designed for conventional manufacturing processes.
3. Do not consider traditional mechanical design principles
4. Reduce the number of parts of assembly by intelligent integration of functions.
5. Check if there are bionic examples to fit the task as these can give a hint towards better design solutions.
6. Use free-form design; as they are no longer difficult to produce
7. Optimize your design towards highest strength and lowest weight
8. Use undercut and hollow structures if they are useful
9. Do not think of tooling as they are no longer required

Yang et.al identifies a few different methodologies set out by other researchers as methods for guiding design by means of following a set of defined rules. Many of the research design rules partially overlap with design guidelines (Yang et.al 2015 p.333). Therefore a careful overlayering of design rules with defined guidelines can be used to develop a valid methodology. It is suggested to always adapt a precise and consistent design methodology when designing a product (Segonds, 2011). Therefore when defined design guidelines overlap with defined design rules, the more clear-cut the methodology for validation.

A standard schema for design methodology is intro-

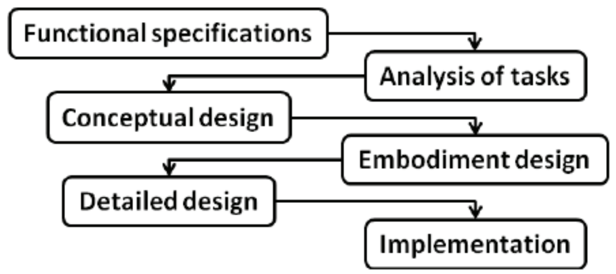


Image: Standard schema of a design methodology (Segonds 2011)

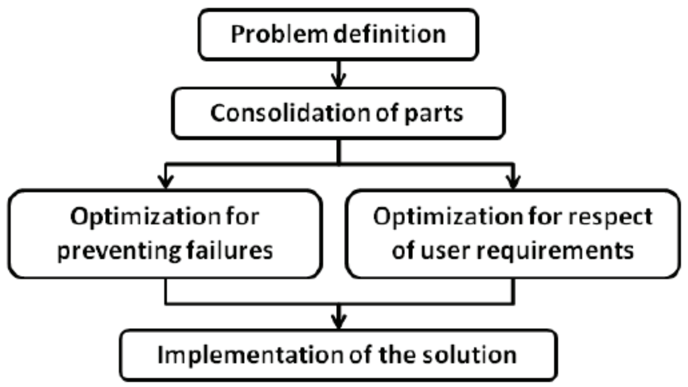


Image: Redesign methodology for AM (Rodrigue 2011) duced in Segounds' text; (segound 2011). A few other design methodologies are also proposed by Rodrigue (2010) and Vayre & Villeneuve (2012); yet neither of these methods are specifically catered to be design methodologies for FDM. The lack of design methodologies specific to FDM and validating FDM prototypes therefore need to be formed.

Rodrigo 2010 suggests incorporating DFM and DFA as methodologies for AM, therefore facilitating the designing of a product to validate and facilitate manufacturing. Rodrigo (2010) suggests the following redesign methodology for AM;

The suggested methodologies then adapted to include both DFM and DFA as parallelle inputs to the formation of the solution. 'The final purpose is to meet end users' needs as accurately as possible' (Boyard; Rivette et.al 2013). It is important to note that the following method assumes 'the needs and the planning tasks' and 'the implementation phase' has already been considered. The 'methodology is consistent from the moment the designer is able to produce a manufacturable digital mock-up, corresponding to a prototype or finished product.' (Boyard; Rivette et.al 2013).

Manufacturing and assembly of designed functional specifications are expected to work hand in hand in the following methodology to complement the accompanying processes rather than to be performed differently in different time frames.(Boyard and Rivette et.al 2013). Fundamental key steps to operationalizing methodology by Boyard and Rivette et.al, (2013) are as follows;

1. Functional specifications
2. Conceptual design
3. Architectural design/ embodiment design phase
4. Detailed design
5. Combination design

The above methodology by Boyard an Rivette has been adapted in the design methodology for this design task by means of incorporating the 5 fundamental key steps in the same order but intercepted by a few other different steps.

CONCEPTUAL DESIGN PHASE (PHASE 2)
Boyard, Rivette et.al (2013) takes each function and sets constraints according to functional specifications. However due to the changing nature of customer requirements 'the extraction of functions from the functional specifications should be flexible and modular to allow for new functions and constraints' (Boyard; Rivette et.al 2013). With focus on design reliability and accuracy for assessing criteria, the following graph of functions is discussed as described most efficiently by the words of Boyard and Rivette et.al. (2013) ;

> *"Since AM can manufacture any type of mechanical part, we assume that for any set of functions there is at least one piece that meets all the functions of this set. A part is defined here as a unitary physical body. The rules for establishing a set are: - Is the part corresponding to this set a wear part? - Can functions be grouped on the same part, or should they be separated? - Are parts movable relative to each other? - ... A set of functions is a collection of functions connected by links. A set must contain at least one function. If all functions of the functional specifications are interconnected to others, then the graph will contain only one set. Sets are interconnected by dotted line representing a fixed hinge between two parts. Each function is represented as a sphere. The spheres are the nodes of the graph. The functions are then linked to each other by segments. These segments represent both direct connections between functions and spatial organization of the functions with each other. Thus, different interconnected functions belong to the same part. In addition, a function A connected to a function B itself connected to a function C indicates that the function B will be found between or will separate functions A and C (Figure 4). This representation allows the user of the methodology to spatially reorganize functions with each other. The advantage is, without conducting discussions of technical solutions, to begin to propose architecture of the final product based only on the functions and constraints to be addressed."(Boyard; Rivette et.al 2013)*

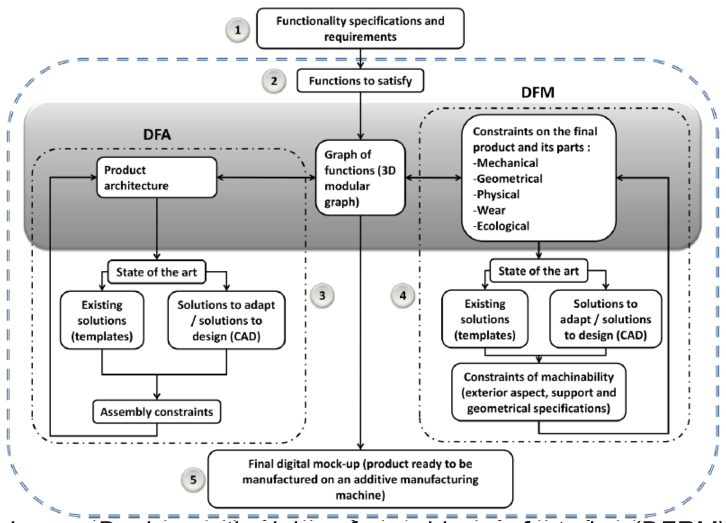


Image: Design methodology for rapid manufacturing (DFRM) (Boyard and Rivette et.al 2013)

WEIGHTING (RELATIVE IMPORTANCE) CRITERIA ACCORDING TO IMPORTANCE

In a traditional work setting, managerial functions and design functions remain disconnected jeopardizing the product quality and quality of production itself with increased costs to cover miscommunication in a demoralised environment (Hauser, Clausing, 1988). However, in contrast to this, Hauser and Clausing deconstruct the House of Quality (HoQ), a design tool for the management of Quality Function Deployment (QFD). HoQ is a platform where marketing, design and manufacturing must come together in reflecting the customs desire.

The House of Quality assess criteria set out for a certain component of the design and orders importance according to primary, secondary and tertiary needs. Therefore weighting criteria according to importance.

An example of an entire House of Quality graph with criteria weighted by relative importance, customer attributes, engineering characteristics and customer perception is shown below. The roof matrix also suggests the combined effort of all teams marketing, design and engineering for the design and realisation of the component set out to be designed.

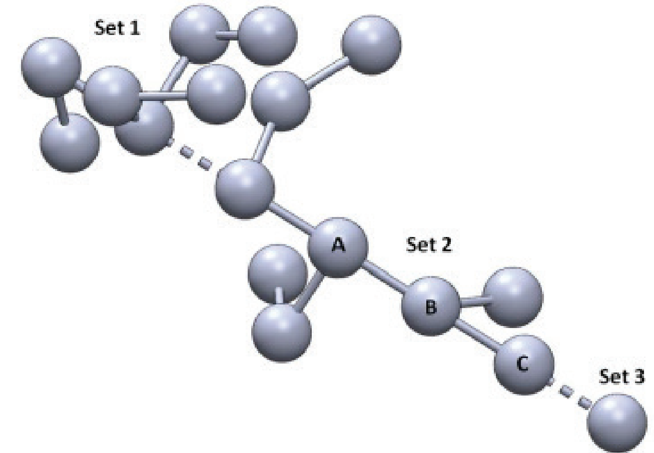


Image : Graph of functions (Boyard; Rivette et.al 2013)

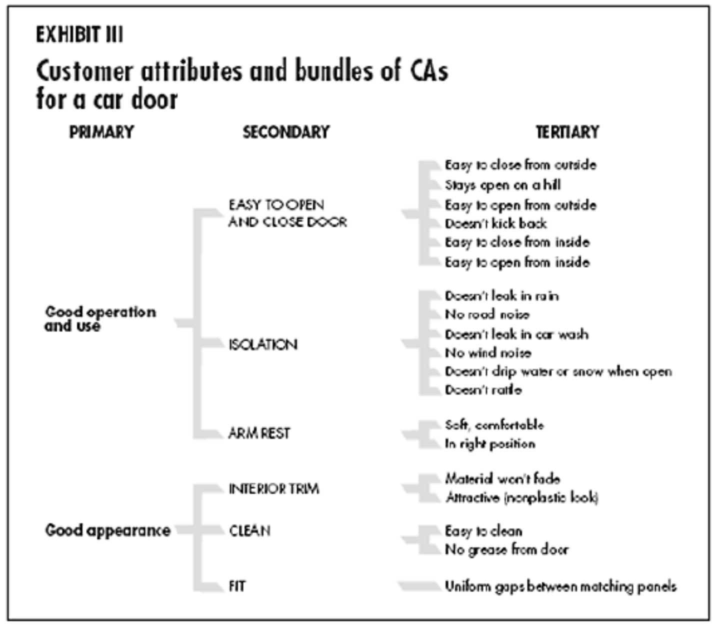


Image: Customer attributes and bundles of CA's for a car door (House of Quality)

Labonnote et.al. suggests the initial research that needs to be carried out in order to design for construction of large scale structures are by setting a well-defined layering of criteria (Labonnote et. al 2016). Further, Practical theories and methodologies are most competent when supported by concrete objectives backed by its own foundations conducted in explicit and detailed processes (Tomiyama et.al 2009). In order to do so, 'identifying the type of building component, the location for production, and the assembly techniques are critical steps to help define the set of criteria (Labonnote et. al 2016). In order to assemble general criteria in a meaningful manner according to the specificities of this project, weighting methods to compare each criteria to another can be an added advantage when proceeding to the validation process. Yeh et.al (1999) reviews Multi-criteria analysis methods that lead to decision making while considering relative importance (weighing) of criteria for a set function (Yeh et.al 1999). The comparison allows for a direct ranking and rating approach by Von Winterfeldt and Edwards (1986) and Tubucanon (1988) that directly correlates to the necessities set out by criteria for this design task. As interpreted by Yeh et.al Winterfeldt and Edwards and Tubucanon's suggestion to first rank all criteria according to their importance, then assign each criteria and estimated numeric value to then propose the relative importance of each such criteria according to its relative degree of importance. Estimated values are then normalized to obtain criteria weights (Yeh et.al 1999).

Gijsberg (2013) adapts a similar method of grading using numerical values to identify relative importance by comparing different criteria to one another. For purposes of not complicating the grading system specific to this case only four fictive criteria are presented (A, B, C and D). Scoring 1 if the criteria in the row is considered more value comparative to the criteria in the column and increasing the score as the priority rises.

The weighting criteria by Gijsbers inspired the weighting criteria adapted to this design assignment. Because Gijsbers uses only 4 criteria to compare each other to, his grading system had to be adapted for more criteria as per needed by the design components of this design assignment. An adaptation of all three methods has allowed for the grading system according to relative importance to be adapted in the Methodology of this design assignment.

SCOREMATRIX VOOR FUNCTIONELE EISEN OP INTERVALNIVEAU

Functionele eisen	A	B	C	D	Totaalscore	C (=n/2)	Totaalscore + Constante
A		5	2	4	11	2	13
B	0		1	5	6	2	8
C	3	4		3	10	2	12
D	1	0	2		3	2	5
(n=4)					30		46

Image: Score matrix for functional requirements at interval level. Gijsbers, 2013

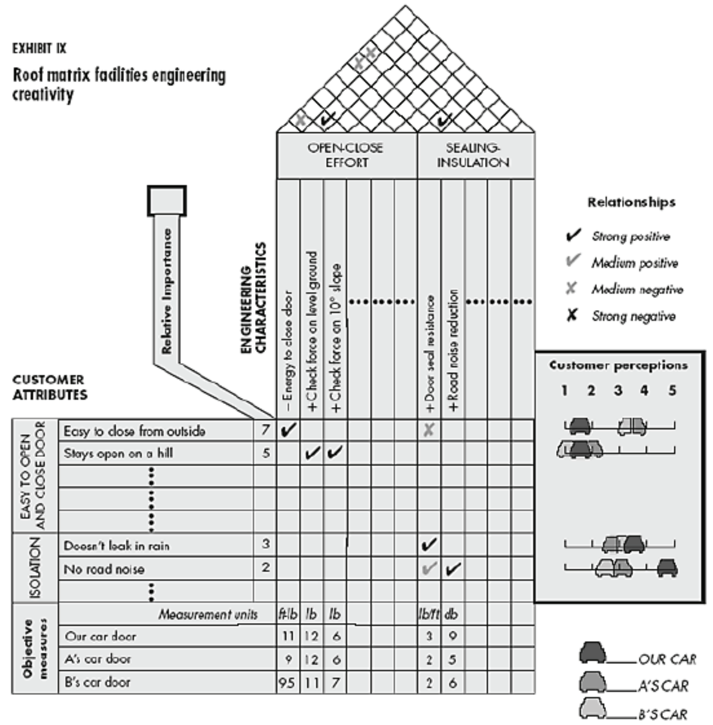


Image: Roof matrix facilities engineering creativity (House of Quality)

SUMMARY

The redesign methodology of Roderigue (2011) incorporating DFM and DFA as both parallel inputs incorporating Design for Manufacture and Assembly (DFMA) as a drive for a more accurate corresponding prototype or finished product will one methodology further used in the adapted methodology for this design assignment. This methodology is further justified by Boyard and Rivette et.al (2013) and their design for manufacturing and assembly methodology model. Boyard and Rivette (2013) further approaches the said functions and sets constraints according to functional specifications. The constraints are therefore needed to be re-ordered in according to their functional necessities.

Yeh et.al reviews multi criteria analysis methods that lead to decision making by considering the relative importance of criteria specific to a function. Gijsberg (2013) uses a grading system for criteria against each other to compare relative importance. The adaptation of all three methods will allow for a redefined set of criteria and methodology specific to this design assignment.

Literature research for the case of this design task was used not only as input for background research but mainly also as a design tool because of the nature of topics researched. In order to successfully design according to manufacture, Additive manufacturing and research based on printing techniques, printing guidelines needed to be considered through literature research. Not just for prototyping but also to set design guidelines, literature research on anthropometric measurements will be used as a tool for designing the measurements of the interior components. Therefore, in the case of this design task, literature research played a large role in being a design tool rather than just contextual studies.

3.6 PROTOTYPING IN THEORY

Prototypes can be perceived differently in different situations according to the necessary function they seek to provide. Prototypes can also be classified according to material and manufacturing properties. All the above mentioned theories will be justified in the following section of literary research.

The types of prototypes described by both Houde & Hill (1997) and Nielsen (1989) are further elaborated on by Lande and Leifer (2009) as the differences in prototyping to be design thinking vs engineering thinking. Engineering prototyping examples to be CAD, Critical function prototypes, Funky System Prototypes and Functional System Prototypes, the above systems drawing out Implementation and integrate according to from the taxonomy of Houde &Hill (1997) and Verticality from the taxonomy of Nielsen(1989).

Houde identifies prototyping in two parts; Funky and functional system prototyping. Funky and functional system prototyping is a two-step method, firstly to identify a system in an efficient and possibly undefined way (funky) secondly to aesthetically modify this system according to display (functional) in a pre-production prototype(Houde and Hill, 1997). Funky system is the process of defining the mechanical, geometric and physical functional specifications with an input of anthropometric measurements used for ergonomics (Houde and Hill, 1997). Also suggested methods of prototyping is CAD prototyping; a much more precise method for engineering prototyping. Informal sketches replace specific CAD drawings and renderings and Critical function prototyping; where systems or subsystems that examine the physicality or mechanism of a selected part of the entire system. Eg: A simple interface of a handle connection (Lande and Leifer 2009)

The perception we have of prototypes can affect the way we see any future prototype. Current terminology and methods define the language used for prototypes simply by their attributes (Houde and HIll 1997). If detrimental preconceptions of prototypes are eliminated, prototyping could reach new levels of innovation with minimal defining boundaries. It is also difficult for a single prototype to reach an understanding of a broad audience, therefore carefully choosing a medium of prototyping for a selected audience is necessary.

Lande and Leifer suggests a T-shaped prototyping model with Design prototypes taking on a more horizontal approach of service features and Engineering prototypes increasing in functionality of features as vertical prototypes. The combination of design prototypes and engineering prototypes lead to a scenario based prototyping.

Houde and Hill suggest their own version of approaching a prototype with a model of what prototypes prototype:

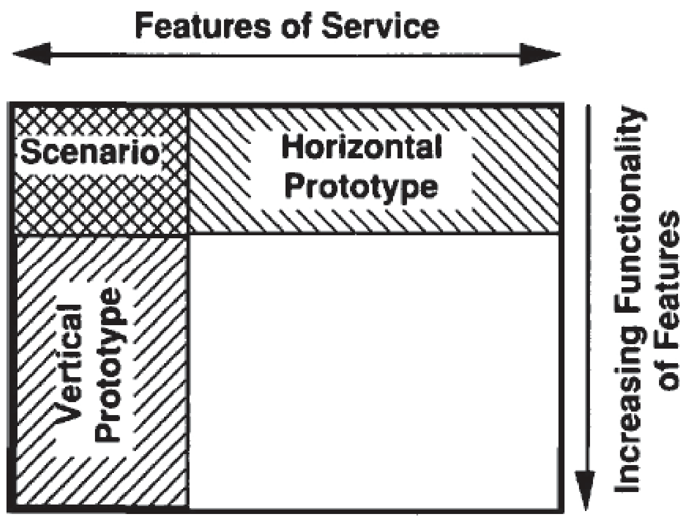


Image: Three type of prototyping, horizontal, vertical and scenario (Nielsen 1989)

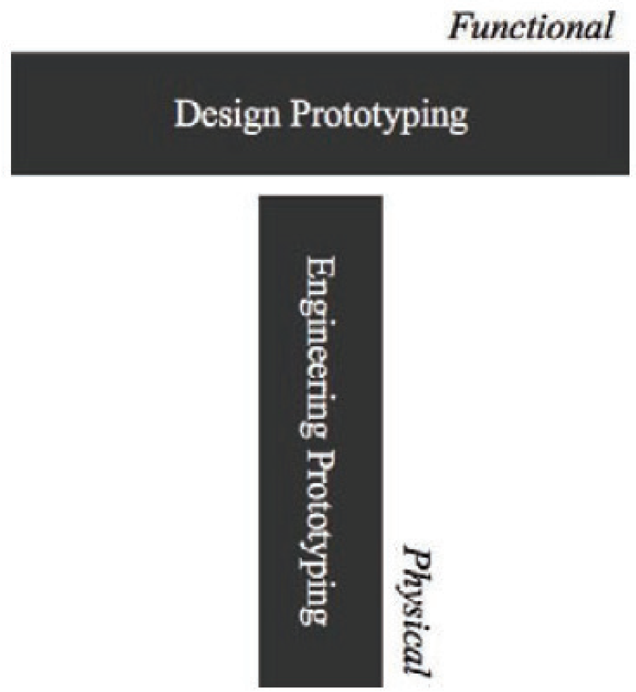


Image: T-Shaped Prototyping model (Lande and Leifer 2009)

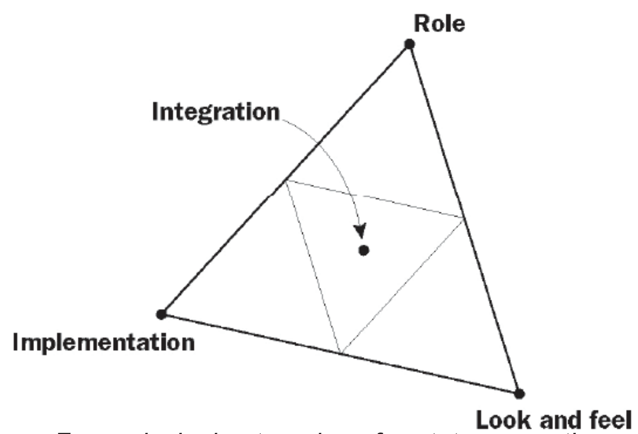


Image: Four principal categories of prototypes on the model of what prototypes prototype. (Houde and Hill 1997)

The model shown represents a 3 dimensional approach to important aspects of an interactive prototype. With definitions being; Role: questions about the use of the artefact in the users life, Look and feel: tactile experiences by the user, aesthetic approach to the artefact, Implementation: the technical aspects of the function, how the artefact actually works. (Houde and Hill, 1997)

The triangular shape of the model represents the inherent importance of all three inputs with neither more important than the other.

> *"Integration prototypes are built to represent the complete user experience of an artifact" (Houde and Hill 1997).*

Therefore, integrated prototypes are to help the designer mimic the most accurate simulation of the final design.

SUMMARY

Most prototype terminology is centered around its attributes; what is used to build it or how they work. This perception limits the capabilities of prototyping as a mode of design representation due to preconceived notions. The role of a prototype on the life of its user, tactile properties, how it should be realised could be three ways of approaching the prototype to benefit an end purpose. Further, by identifying the principle behind the function may lead to more innovative methods of solving and realising a prototype.

Informal sketched are replaced by CAD drawings for more precise and accurate prototypes. Engineering prototyping such as CAD drawings, critical functioning prototype, funky and functional systems prototypes are influenced by the taxonomy of Houde and Hill (1997) and taxonomy of Nielsen (1989). Funky systems prototyping being identification of systems in an efficient and possibly undefined way while Functional systems prototyping is modifying these systems according to function. Funky and functional systems prototyping as explained by Houde and Hill will be incorporated in two stages of the design methodology for this design task due to their ability to define different systems that wouldn't be defined in common scientific research.

ERGONOMICS

Ergonomic parameters will be used as a design tool in the designing of transformable interiors. Ergonomics is defined as the name given to the process of designing according to human needs, in order to optimize well being and overall system performance. (Morris 2009). Two relevant branches of ergonomics to be considered in this design task could be; Cognitive ergonomics that cover aspects of aesthetics, expectations, perception and sensory satisfaction(Morris 2009) and Affective design which is a Branch of ergonomic thinking that is concerned with the emotional effect that a product has on a user based on their interaction with it. If a person has strong enough emotional attachment to a product being that,they are less likely to 'throw it away' (Morris 2009, P.89).

ANTHROPOMETRIC MEASUREMENTS

Anthropomorphic measurements according to the National Center for Biological Information (NCBI), US are a series of quantitative measurements of human body with core measurements being height, weight etc. (Casadei and Kiel 2019)These measurements aid architectural and product design where designed purely for human use allowing for improved product or spatial design. Anthropomorphic measurements aid ergonomic design as a design tool. Anthropometric measurements are intensively used in the field of Ergonomics to improve user satisfaction, minimal to no human error and maximum efficiency in any given circumstance (Panero and Zelnik 1979 p.19).

Although ergonomics is widely used in the field of design as a guideline for human needs, it is possible that these designed products not only are functional but also has considered to a certain extent, aesthetic and user comfort. Therefore Cognitive ergonomics is described by Morris as a tool used in product design to "cover aspects of aesthetics, expectations, perception and sensory satisfaction" (Morris 2009). Further according to Ergo-Plus (a software and deliver service company with a mission to empower companies to build safer, healthier, more productive worksites) describes cognitive ergonomics as; "the field of study that focuses on how well the use of a product matches the cognitive capabilities of users. It draws on knowledge of human perception, mental processing, and memory. Rather than being a design discipline, it is a source of knowledge for designers to use as guidelines for ensuring good usability." (ErgoPlus)

With the aid of anthropometric information, it is possible to obtain relevant body type information to aid any architectural or product design process where the human is the primal design object based on. Incorporating quantitative information as such will most definitely lead to an improvement of the space designed.

From the early days of design, influential architects, designers, mathematicians have valued the importance

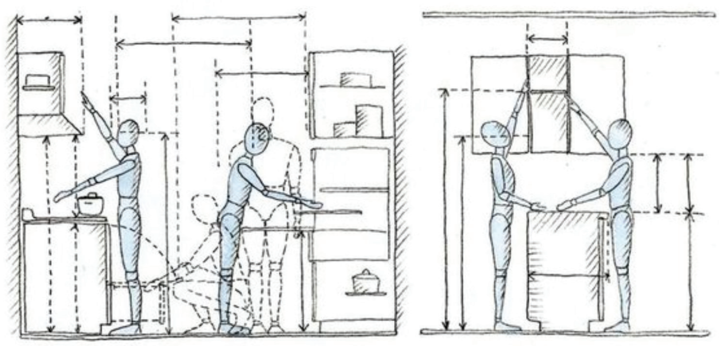


Image: Overlay sketch of Human dimensions and interior spaces (own illustration based on Human Dimension & Interior Space 1979) of incorporating human bodily dimensions and proportions through their work. Fine examples are Leonardo da Vinci's famous drawing of the human figure based on the Vitruvian Norm-Man during the Renaissance, Mid 19th century John Gibson and James Bonomi with a reconstructed vitruvian man and more significant to the current architectural world, more than 2000 years after Vitruvius and his ten books on architecture, Le Corbusier reinstated the relevance of the Vitruvian norm with his Modular figure (Modular no.1). In the 16th century Luca Piccoli, one of the most influential mathematicians of the time and also a friend of Da Vinci's', having written a book about the Divina Proportione (Divine proportion) contends of aesthetic principles found in architecture are also to be found in the human body and even in the latin alphabet. Impactful individuals as such claiming that the proportions of the Golden section to be far superior to all other proportions becomes a solidified argument when seeing it being incorporated in Renaissance architecture, architectural antiquities, as well as the Middle ages. (Panero and Zelnik 1979 p.17-18)

Over the past few decades, dominant architects such as Le Corbusier, having incorporating human dimensions and body measurements as a critical design factor has been a significant statement and design factor. Most dominant in the field of human factor engineering as in the United States or Ergonomics as referred to in Europe (Panero and Zelnik 1979 p.18). Any and all designed functions that require human factors input, say it be architecture, product design or even machine design would require a dominant and consistent reference to Ergonomics as a design factor. Facilitating minimal to no human error with maximum efficiency under any given circumstances. (Panero and Zelnik 1979 p.19)

Ergonomic fit or 'ergo-fitting' having been dominantly used in military applications and machine design, the more mundane tasks of everyday use such as housing, offices, schools, health facilities and public spaces have been rarely informed by such measurements. Ironically, designing for humans, influenced by human proportions suitable for the specific types of humans have not yet been given due prominence, although basic rule of thumb is that being mostly used. (Panero and Zelnik 1979 p.19)

Despite ergonomics being given little significance as a design tool, the design of an interior environment or 'ergofit' must ensure comfort, safety and efficiency of any surface directly used by the individual/ individuals by the space is being designed for. When measurements for surfaces and objects used for basic functions by humans are set to the human bodily proportions, functions become intuitive to use. If an object is at a height proportionate to that of what humans use to sit or sleep on, according to intuition, it is likely that humans will use the designs based on ergonomics to simply sit or sleep on accordingly. Therefore the designer should focus on designing with proportions intuitive to one or more functions without defining each function individually.

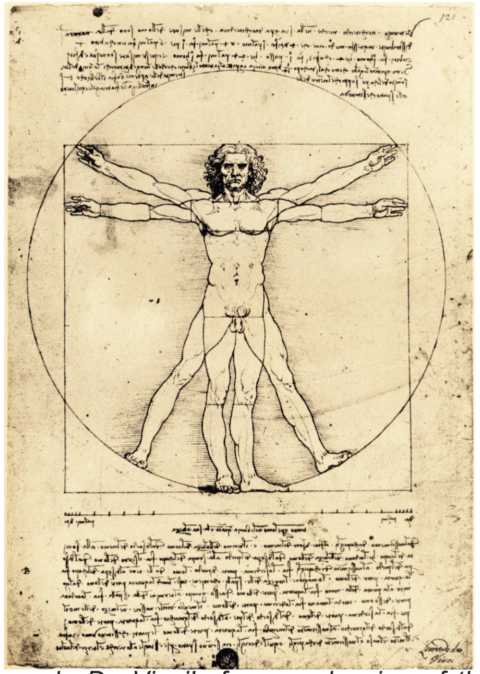


Image: Leonardo Da Vinci's famous drawing of the human figure based on the Vitruvian Norm-man (Bettmann Archive, Inc.)

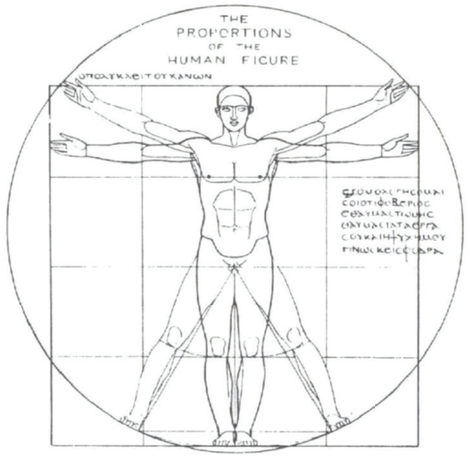


Image: Vitruvian man by John Gibson and J Bonomi, London, 1857 (Human dimension & Interior space 1979)

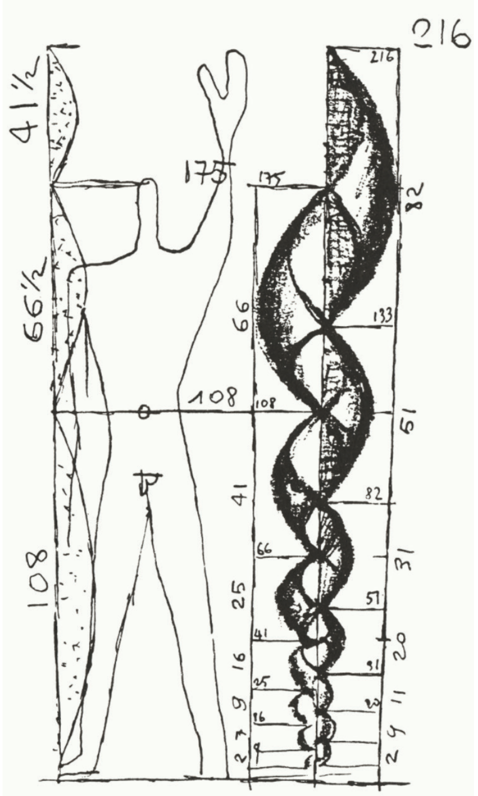


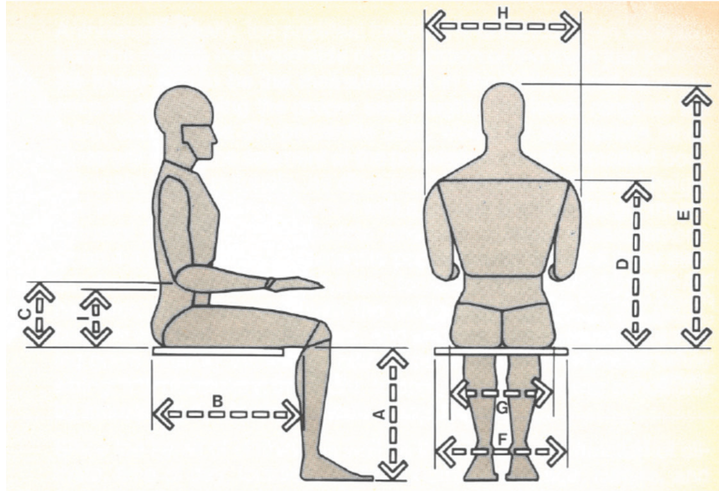
Image: Modular figure by Le Corbusier

EXAMPLE: ANTHROPOMETRICS OF SITTING

If the principles of the functions are to be designed for a start could be to look for open ended definitions such as Branton's take on sitting as; "the sitting body, therefore, is not merely an inert bag of bones dumped for a time in a seat, but a living organism in a dynamic state of continuous activity" (Branton 1966 p.29). "It has also been contended that the many postures assumed while sitting are attempts to use the body as a lever system in an effort to counterbalance the weight of the head and trunk" this identifies as a body's attempt to stabilize (Panero and Zelnik 1979 p.59)

Aa few functional requirements to consider when designing seating without defining the design could be as follows;

1. When sitting, about 75 percent of your total body weight is supported on only 26 sq cm of the lowest point of the ischial tuberosities on the surface of the seat (NCHS 1965).
2. Propper padding on the seat needs to provide equal distribution of the body weight supported by the ischial tuberosities and allow for the sitter to change positions when necessary to alleviate discomfort.
3. Must be based only on selected anthropometric data since there is no guarantee that an anthropomorphically correct chair will be comfortable for all users (Panero and Zelnik 1979 p.60).
4. Must have foot and back rests as the absence of them will increase body instability and additional muscular forces would have to be exerted to maintain proper equilibrium. Therefore causing fatigue and discomfort (Panero and Zelnik 1979 p.60)
5. Basic dimensions required for designing a seat are (Panero and Zelnik 1979 p.60);
   a Seat height
   b Seat depth
   c Seat width
   d Backrest height
   e Armrest height
   f Spacing
6. A tall person would be far more comfortable using a chair with a low seat height comparable to a short person using a chair with a seat that is too high (Panero and Zelnik 1979 p.60)
7. A seat depth of 43.2 cm for an easy chair would accommodate about 95 percent of all users. (Panero and Zelnik 1979 p.65)
8. Back support; somewhere in between just lumbar support and extending all the way to the nape of the neck would suffice for general seating purposes



MEASUREMENT	MEN Percentile 5 in	MEN 5 cm	MEN 95 in	MEN 95 cm	WOMEN Percentile 5 in	WOMEN 5 cm	WOMEN 95 in	WOMEN 95 cm
A Popliteal Height	15.5	39.4	19.3	49.0	14.0	35.6	17.5	44.5
B Buttock-Popliteal Length	17.3	43.9	21.6	54.9	17.0	43.2	21.0	53.3
C Elbow Rest Height	7.4	18.8	11.6	29.5	7.1	18.0	11.0	27.9
D Shoulder Height	21.0	53.3	25.0	63.5	18.0	45.7	25.0	63.5
E Sitting Height Normal	31.6	80.3	36.6	93.0	29.6	75.2	34.7	88.1
F Elbow-to-Elbow Breadth	13.7	34.8	19.9	50.5	12.3	31.2	19.3	49.0
G Hip Breadth	12.2	31.0	15.9	40.4	12.3	31.2	17.1	43.4
H Shoulder Breadth	17.0	43.2	19.0	48.3	13.0	33.0	19.0	48.3
I Lumbar Height	See Note.							

Image: Key anthropometric dimensions required for chair design (Human Dimension & Interior Space 1979)

SUMMARY

Anthropometric measurements used for ergonomic design will be used in this design assignment. Anthropometric information according to National Center of Biology Information, US (NCBI) is a series of quantitative measurements of a human body with core measurements being height, weight etc. Ergonomic design is a method of designing according to human needs in order for optimization and overall system performance. Branches of ergonomics such as cognitive ergonomics and Affective design could also be considered in the design task as methods for considering tactile and aesthetic properties of the design.

The notion of starring human dimensions in design can be seen as early as the 16th century through Luca Piccolis book about the Divine Proportion. One of the more recent uses of such methods can be seen through Le Corbusier and his Modular Figure (Modular no.1) and his prominent use of human dimension through architectural designs. Machine, military application and product design strongly still, use ergonomics as a viable design input.
By incorporating anthropometric information and ergonomic design, designing for human scale can be optimal and precise. Anthropometric measurements used in ergonomics will further allow for the interior furniture to be designed specifically according to optimal human measurements allowing for the designed furniture to be transformable where seen fit by the user. Adaptability and transformability will naturally occur if the designed furniture is not defined by its function but merely guided by intuitive human measurements; allowing for one piece of furniture to be used in multiple ways according to how the user perceives the space according to whichever function required at the time.

Anthropometrics can facilitate the use of objects as directed by intuitive human measurements. Due to the necessity of this design task to designing furniture without defined functions will require the use of ergonomics.

To incorporate the above research with the design assignment, firstly, Cognitive ergonomics will be considered a design strategy for achieving the functional specifications and detail design for the interior of the adaptable living modules. Anthropometric information obtained via liable literary resources will be used as a design tool to set universal measurements for the transformable interior surfaces. Cognitive ergonomics using anthropometric measurements will allow for the design to adapt to varying human movements where seen suitable by the user.

4. ORGANIZATION

In order to carry out a successful start to end of this hypothesis, the process of design inputs, designing according to a methodology, printing, testing and validation were carefully considered and adapted specific to the unique needs of this design task. As described in the previous chapters, Design by research is considered a main design input while the entire design process is carefully guided by a specific methodology.

The methodology used for this design task was carefully put together with similar processes that exist and processes that were designed purely for validation of FDM components and manufacturing processes.

For the organization of this project, it was essential to develop the functional aspects of the design along with the conceptual development to have a successful output of transformable connections. The combined development will be further explained in the methodology and shown by example in the design process later through this report. Due to all aspects of the methodology having a direct or indirect impact on each actor contributing to a whole and complete design, a lot of back and forth between different components of the methodology was to happen. All components giving feedback to one another lead to the need of a guided method of validating these ideas and constraints. The methodology section will explain in detail how each component will influence another.

FDM using recycled PET will be the main source of prototyping for validation of the designed transformable connections.

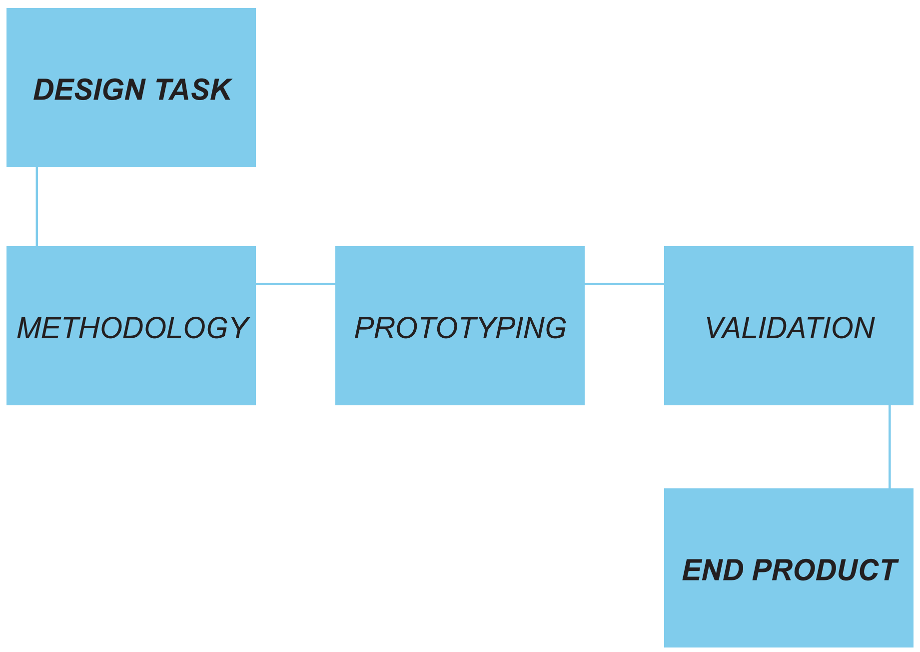


Image: Organization schematics (own illustration)

5. METHODOLOGY FOR THESIS VALIDATION

METHODOLOGY [A DESCRIPTION OF THE METHODS AND TECHNIQUES OF RESEARCH AND DESIGN, WHICH ARE GOING TO BE UTILIZED.]

It is suggested to always adapt a precise and consistent design methodology when designing a product (Segonds, 2011), therefore the following methodology has been carefully iterated and adapted by methodologies of Winterfeldt, Edwards (1986) and Tabucanon (1988) interpreted by Yeh et.al (1999), Boyard, Rivette et.al (2013) and Rodrigue (2010).

The reasoning for adapting a new approach by combining adapted methodologies is due to the minimal availability of scientific research done under the particular topic of 'FDM of transformable furniture using recycled PET', the need to physically test and validate the transformability of the furniture according to specific criteria for each individual components, to make maximum use out of rapid prototyping and to have an end result of 1:1 prototype of the final design iteration.

The following methodology is an early version. **The methodology was subjected to minor changes and adaptations throughout the design process, due to the design process and methodology being dependent on each other. The adaptations have been highlighted in the pink boxes.** The adaptations are the exact way this design task was carried out. The older methodology has been provided in this thesis for the purposes of being adapted by different design tasks when needed. Further details of how the methodology has been implemented through the design task will be shown in the research by design phase of this report.

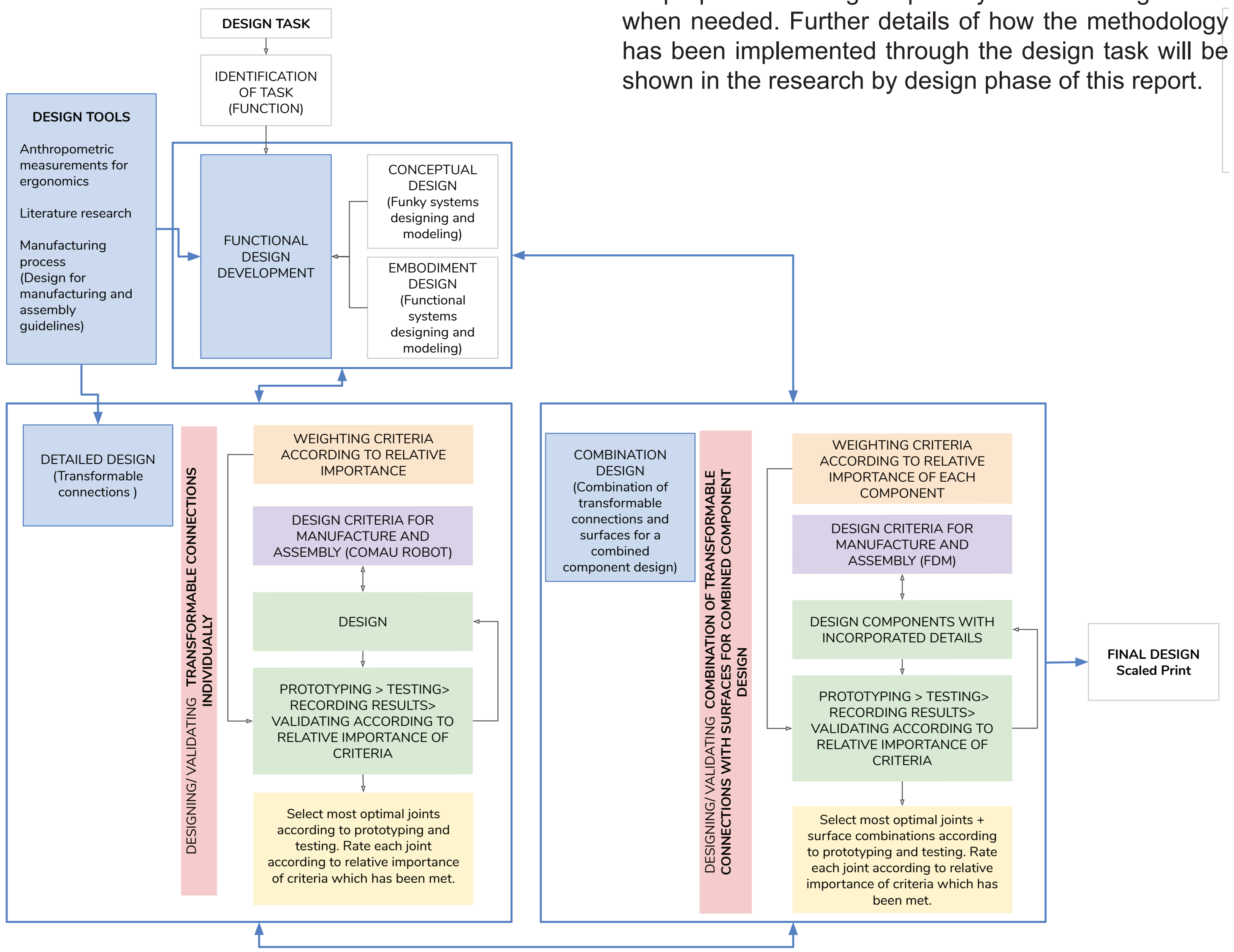
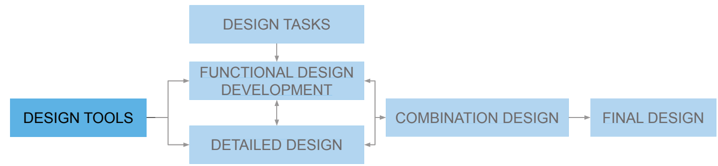


Image: Final methodology after being adapted to changes according to the design process. (Own illustration)

5.1 LITERATURE RESEARCH AS A DESIGN TOOL



**Design tools (Explanation as to why literature research is used as a design tool can be found under the summary for methodology literature research.)

A. BACKGROUND RESEARCH TO VALIDATE DESIGN ASSIGNMENT*

(Explained in the Literature research section)

B. ANTHROPOMETRIC MEASUREMENTS AND COGNITIVE ERGONOMICS *

Anthropometric measurements are intensively used in the field of Ergonomics to improve user satisfaction, minimal to no human error and maximum efficiency in any given circumstance (Panero and Zelnik 1979, p.19)

Anthropometric measurements used in ergonomics will allow for the interior furniture to be designed specifically according to optimal human measurements allowing for the designed furniture to be transformable where seen fit by the user.

Adaptability and transformability will naturally occur if the designed furniture is not specified by its function but merely guided by intuitive human measurements. This, allowing for one piece of furniture to be used in multiple ways according to how the user perceives the furniture, according to whichever function is required at the time.

5.1.1 ADAPTATION

Design tools used for the completion of the design task were as follows;

A. LITERATURE RESEARCH ON SPECIFIC TOPICS;

Literature research was conducted on a few topics which were specific to this design task such as;

1. Additive manufacturing and the specifics of the manufacturing process
2. Fused deposition modeling (FDM) and design build approach
3. Case studies for additive manufacturing of similar projects
4. Design research
5. Design manufacturing
6. Existing design methodologies for similar processes and similar validation methods
7. Prototyping in theory
8. Ergonomics
9. Anthropometric measurements

Topics such as sustainability and the climate crisis due to the excessive consumption of plastic by society were not further looked into as they are proven topics of research with existing content that can be used as a reference in this design task if necessary.

B. ANTHROPOMETRIC MEASUREMENTS AND ERGONOMIC MOVEMENT

Anthropometric measurements used in ergonomics will allow for the interior furniture to be designed specifically according to optimal human measurements. Therefore the designed furniture will be transformable where seen fit by the user.

Adaptability and transformability will naturally occur if the designed furniture is not specified by its function but merely guided by intuitive human measurements. This, allowing for one piece of furniture to be used in multiple ways according to how the user perceives the furniture, according to whichever function is required at the time.

C. BACKGROUND VALIDATION

In order to give this design task a context for conceptual and contextual development a generic background based on the idea of a tiny house was introduced. This concept will be described in detail under the Background context of Research by design page 62

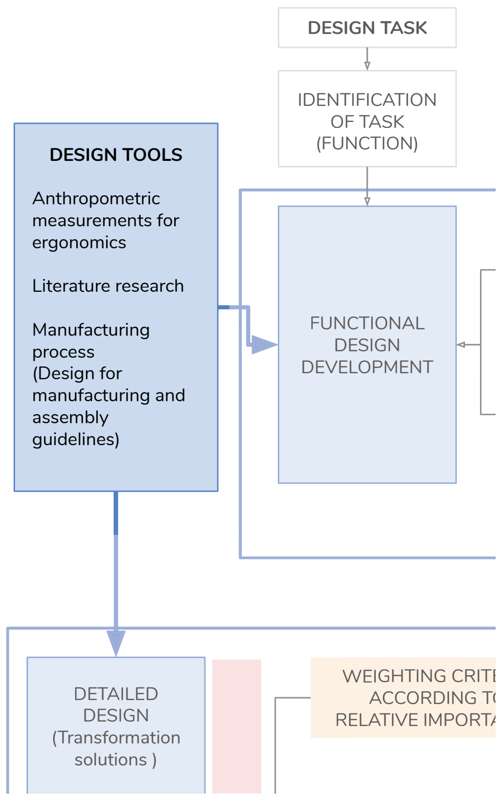
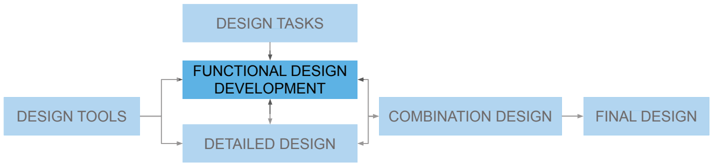


Image: literature research and other design tools with its connection to other design stages (Own illustration)

5.2 RESEARCH BY DESIGN (STAGE 1, 2 & 3)



The main approach to this design project will be through research by design. The following sub steps will each follow similar methodologies to one another adapted by different methodologies (further detail explained in the report) which have been proven. Conceptual design and Functional design (Stage 2 & 3)The conceptual design phase identifies the functional design components. With the aim of not specifying or defining the different furniture design, a few different heights of supports will be based on to be further developed.

Anthropometric measurements will be used as a base design tool. Specifications are drawn out from Human Dimensions and Interior Spaces by Panero and Zelnik (1979) and Architects Data by Ernst and Neufert (2000). Post Stage 1, surfaces will be conceptually designed according to the available data from design tools in Stage 2. Surfaces will be designed according to its embodiment and tactile properties expected by the user in stage 3. Once designed, each component can be prototyped (in a smaller scale for testing) by either using additive manufacturing or hand made models according to necessity. To aid with conceptual prototyping Houde's Funky and Functional systems prototyping will be incorporated.

Houde identifies prototyping in two parts; Funky and functional system prototyping. Firstly, to identify a system in an efficient and possibly undefined way (funky) then aesthetically modify this system according to display (functional) in a pre-production prototype (Houde and Hill, 1997). Funky systems is the process of defining the mechanical, geometric and physical functional specifications with an input of anthropometric measurements used for ergonomics (Houde and Hill, 1997).

In the conceptual design phase (Stage 2), anthropomorphic information and the basic tactile needs will be considered when designing surfaces and forms of furniture. Below shows a detailed flow chart of the conceptual design phase. Parallel to the conceptual design phase, Embodiment designing (Phase 3) of surfaces will occur.

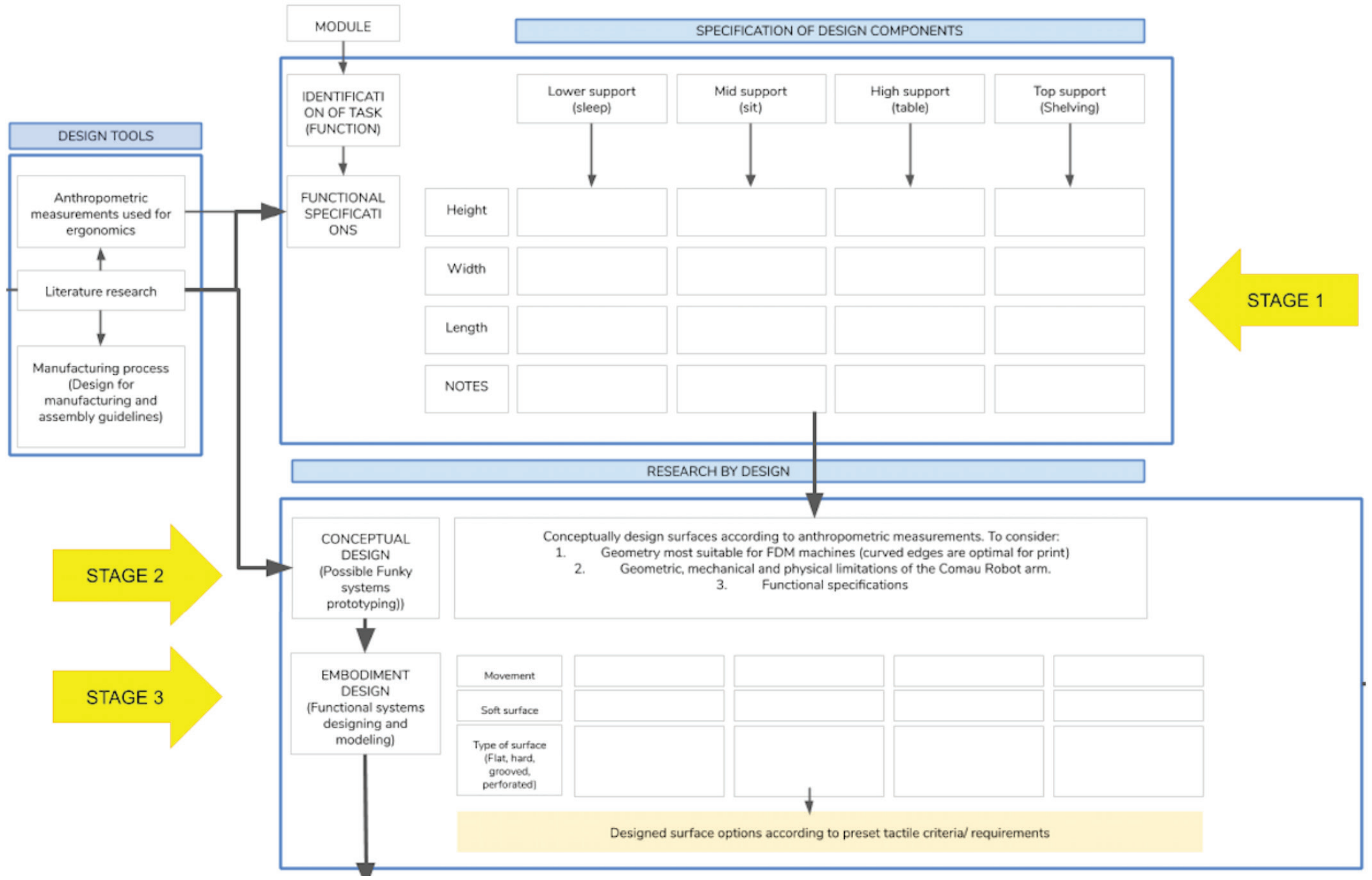


Table 1: Dominant design tools, Stage 1: specification of the design components, Stage 2: conceptual design phase, Stage 3: Embodiment design of the Methodology (own illustration)

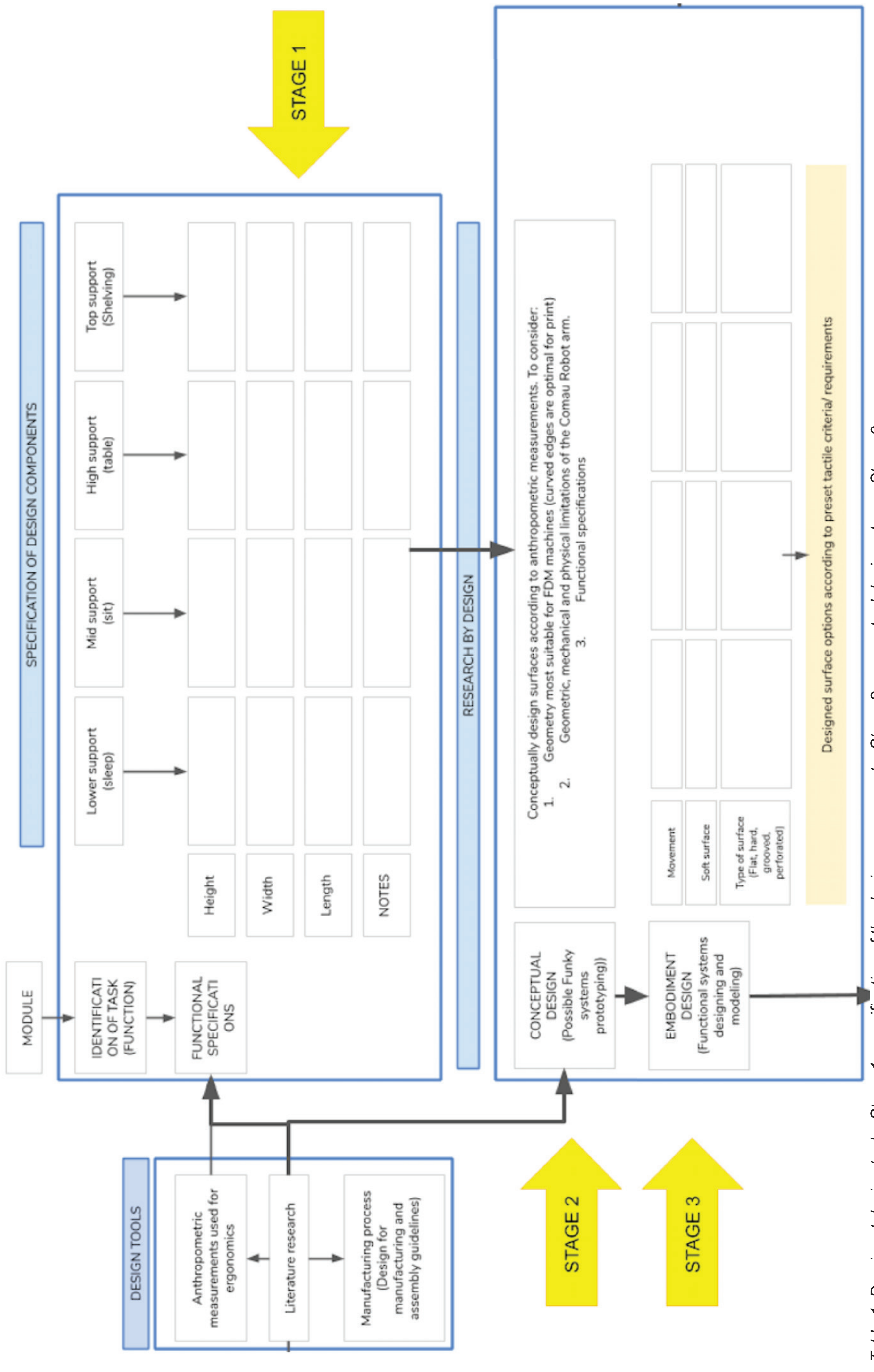


Table 1: Dominant design tools, Stage 1: specification of the design components, Stage 2: conceptual design phase, Stage 3: Embodiment design of the Methodology (own illustration)

5.2.1 PARALLEL DEVELOPMENT OF FUNCTIONAL DESIGN AND DETAILED DESIGN

As explained in the section of Design requirements based on the design task p.xx a transformable connection system for adaptable design will be the focus for function design and detailed design. Detail design will be given more priority.

In order for the details of the transformable connections to be designed, they need to be influenced by the load, direction, material of what they will be supporting through this connection. In order to have a solid context to base the transformable connections on, functional design development was conducted.

Functional design in the case of this design task will be designing of the surfaces based on dimensions of ergonomic design. Once these dimensions are set in place, a clear context is provided as to what the transformable connections need to entail. As a sub design strategy the conceptual design of the design task will be considered an input to the functional design of this design

Considering the context of the whole project being a tiny home as explained in the background context of this report and the context to the functions being provided by ergonomic measurements, a clear direction is given to the designing of the transformable connections.

Therefore, when considering steps for the design task, it is vital that development of the functional design needs to occur hand in hand with the detail design informing on another about the constraints and necessary design goals that needed to be achieved. The following is a simplified version of the design methodology portraying the parallel development of Functional design and Detailed design influenced by the main context of this de

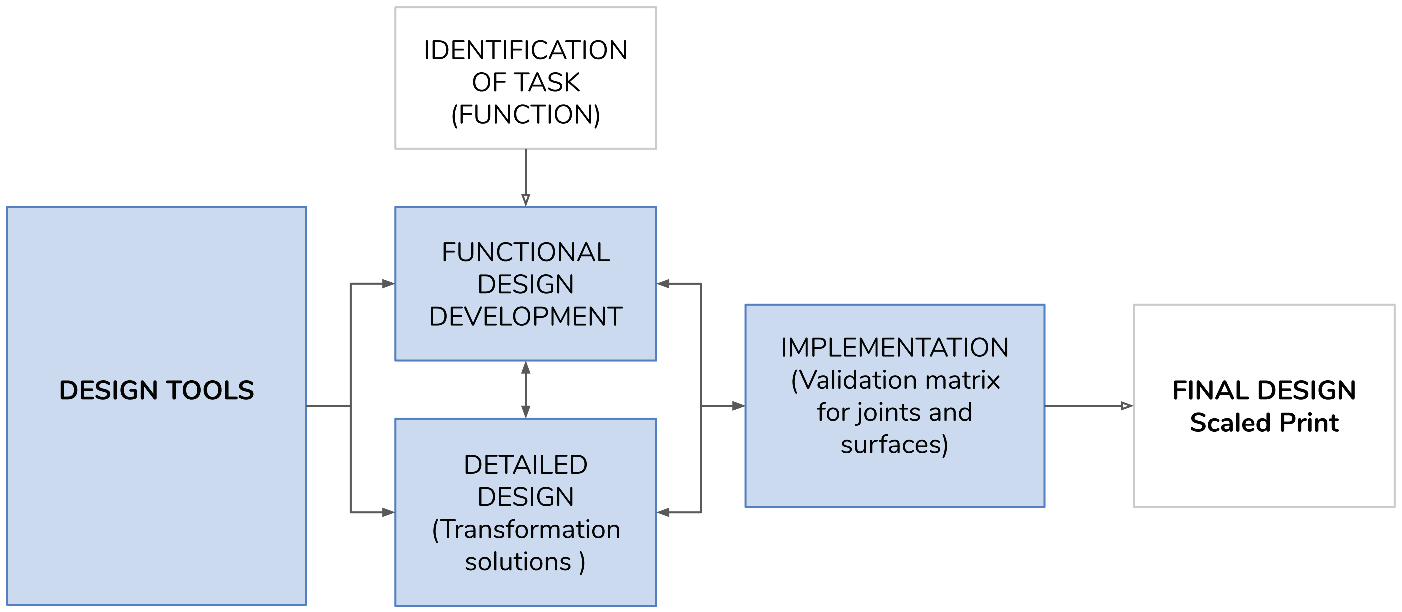


Image: Summarized version of methodology representing paralleled development of design steps. (own illustration)

5.2.2 ADAPTATION

Through the realization of this project, it was decided upon focusing the design on transformable connections rather than designing individual pieces of furniture, therefore slight changes to the above stages were made as highlighted and described under each stage for the proposed methodology.

Stage 1: Rather than identifying tasks, possible ergonomic measurements were taken into consideration on different dimensions for different possible groups of functions. This change from different measurements of heights to dimensions of group of functions were due to the overlapping of many functions as observed in ergonomics. The graph below demonstrates the adaptation of the stages 1,2 and 3 in a more combined approach as the three stages overlapped in its design process.

Stages 1,2 and 3 were combined ad divided as the table below.
Through the design process it was important for the conceptual development to occur on par with Embodiment design. Conceptual design was divided under the following categories;

1. Contextual Development for the background of design task.
2. Design constraints based on functional development. (further detailed in the research by design process p.67)
3. Design constraints based on conceptual development. (further detailed in the research by design process p.67)

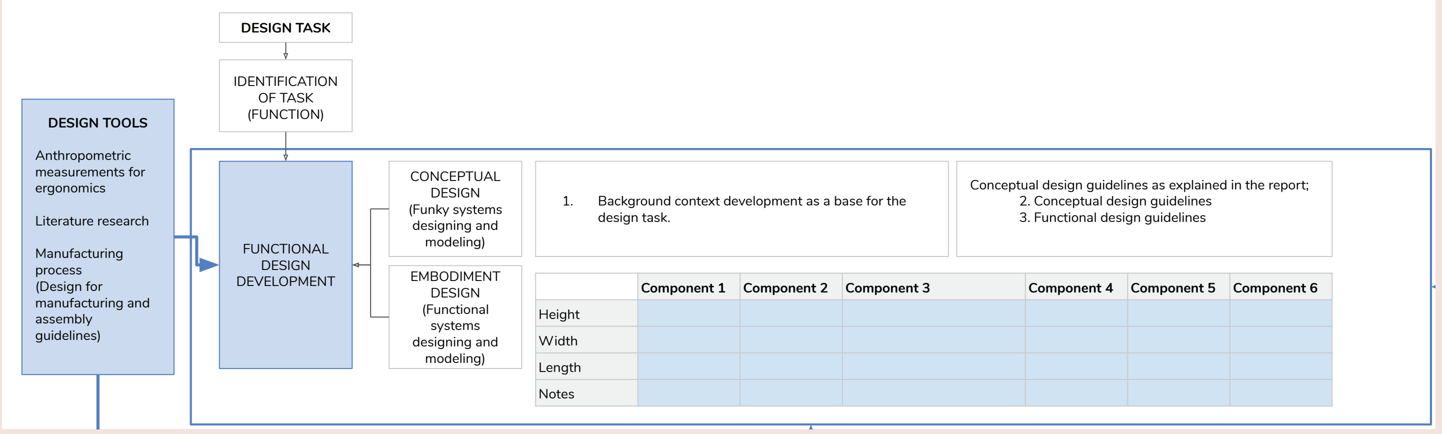


Table : Functional design development in detail (own illustration)

CONCEPTUAL DESIGN

Contextual Development:
In order to give the design task a fulfilling context, a background design needed to be made. A few tiny homes based in the Netherlands were taken as case studies and as a base for regulations and measurements for tiny houses. After observing the case studies, basic guidelines for a tiny house were designed. (Further details elaborated under Background context page 62)

Embodiment design for functional design development:

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
	Box shelf	*Small shelf*	*Universal component*	*Wide shelf*	*Vertical support*	*Roller box*
Height	35	35	20	45	60	42
Width	35	30	1	6	6	42
Length	35	30	15	90	90	62
Notes	illustration 6	30cm according to wall grid, Ill 6	Universal component is to have holes printed in specific places to allow other components such as televisions and photographs to be mounted on	Illustration 2,3,4,6	Illustration 7	illustration 1,5

Table : Numeric of specified functional measurements (own illustration)

The above components will be further designed aesthetically hand in hand with the conceptual development phase.

Functional specifications are drawn out from ergonomic diagrams and anthropometric measurements. These measurements are drawn out from overlapping of functions due to human measurements and intuitive patterns of human movement. From the start of this project, aesthetic qualities of the final design was seen as a priority. Therefore hand in hand with the functional specifications, conceptual development needed to occur. Purely due to the possibility of combining functions with aesthetics.
The following diagram shows the division of components according to different basic functions. All functions attempt at not defining the exact function, but to allow the user to see function as he pleases.
The table numerically demonstrates the overlapping of functions and specific dimensions required for each function accordingly. Showing references.

It was also adapted rather than having functional design, conceptual design and embodiment design as separate parts, for these to be partially combined in the following order for a smooth communication between the three design strategies. Long with the growth of functional design, conceptual design needed to occur hand in hand for a combined development of the design.

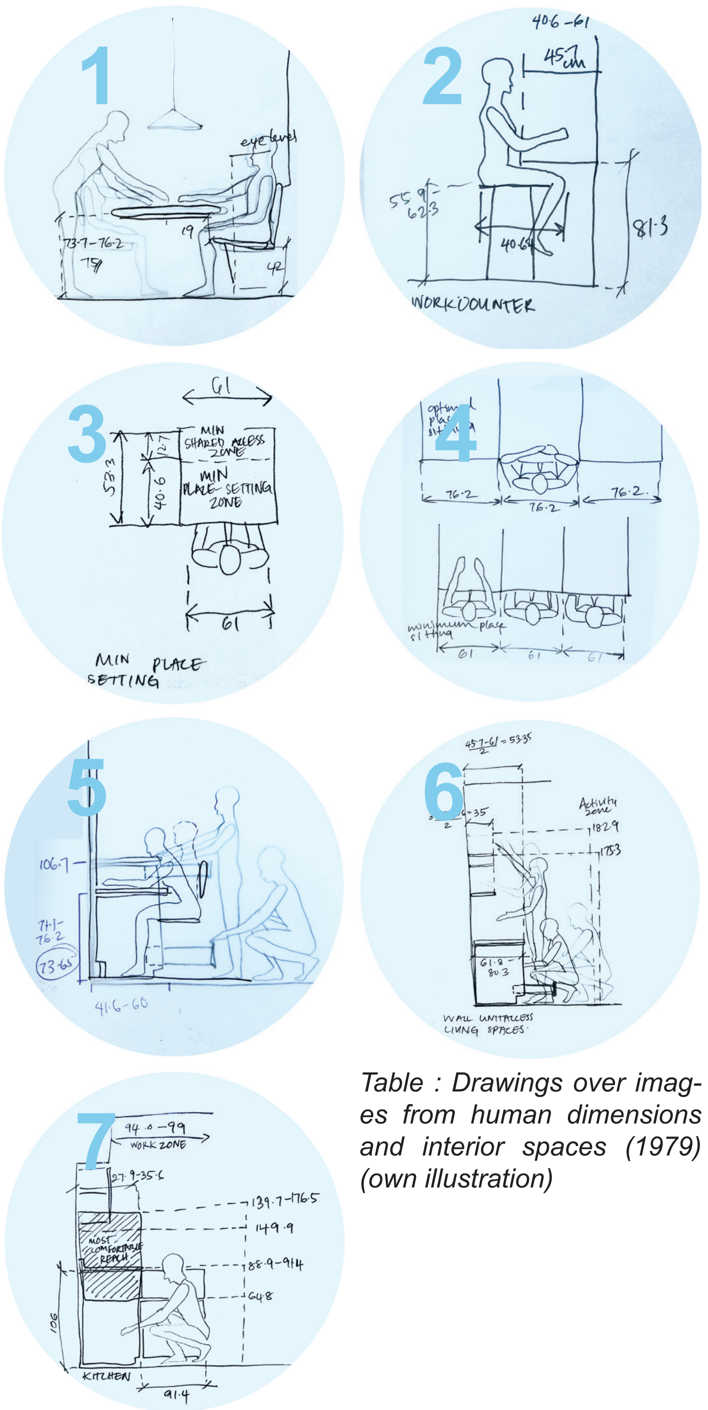
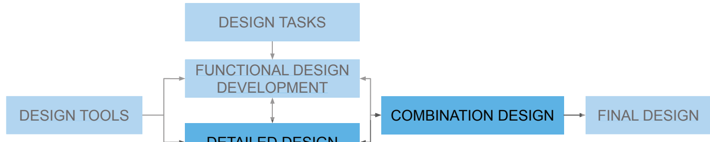


Table : Drawings over images from human dimensions and interior spaces (1979) (own illustration)

5.3 DESIGNING FOR VALIDATION USING PROTOTYPES



A. WEIGHTING CRITERIA ACCORDING TO RELATIVE IMPORTANCE (STAGE 4)

To design detailed transformable connections and connections, a list of criteria was defined. The wide range of criteria weighted according to relative importance against each other will simplify the design process and allow for an efficient validation of prioritized criteria.
In order to compare one criteria to another, multi-criteria analysis methods by Winterfeldt, Edwards (1986) and Tabucanon (1988) interpreted by Yeh et.al (1999) and Gijsber (2011) score matrix for functional requirements were used as inspiration and adapted for the needs of this design assignment.

SCOREMATRIX VOOR FUNCTIONELE EISEN OP INTERVALNIVEAU							
Functionele eisen	A	B	C	D	Totaalscore	C (=n/2)	Totaalscore + Constante
A		5	2	4	11	2	13
B	0		1	5	6	2	8
C	3	4		3	10	2	12
D	1	0	2		3	2	5
(n=4)					30		46

Table 2: Score matrix for functional requirements at interval level. (Gijsbers, 2013)

RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA	Direction	Load bearing	Number of movement per lifespan	Bending radius	Expandability	Transformation distance	Single person handling	TOTAL SCORE
Direction								
Load bearing								
Number of movements per lifespan								
Bending radius								
Expandability								
Transformation distance								
Single person handling								
0- less important 1- equally important 2- More important								

Table 3: Adapted score matrix for Detail design phase (Stage 4) (Own Illustration)

B. DESIGNING FOR ASSEMBLY AND MANUFACTURING ACCORDING TO FDM MACHINE CRITERIA

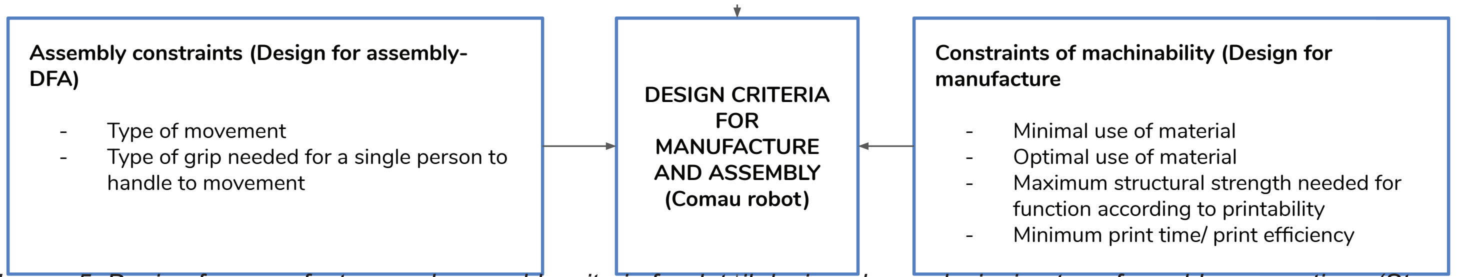


Image 5: Design for manufacture and assembly criteria for detail design phase, designing transformable connections (Stage 5) (Own illustration)

Assembly constraints (Design for Assembly DFA) and Constraints of machinability (Design for manufacture DFM) specific to the Comau robot arm, Design for Manufacture and Assembly (DFMA) will be considered when continuing the design. A few considerations are shown in Image 5.

It is vital that from the conceptual design phase that the design is informed by the manufacturing process. The overall design needs to be aware of the machinability. As an example; Rounded edges are more optimal for print time and material strength compared to straight edges. Such intelligence could be gathered via literature research, observing previous designs for fused deposition modeling or most effectively through prototyping and testing.

Although many examples can be found via existing projects, there is limited information to compare the possibilities of recycled PET as a material used for fused deposition modeling at this scale. Therefore optimizing for print and material use, iterating for developments and continuing a circular process of designing through research will be adapted in the coming process of validation.

C. VALIDATION MATRIX USING PROTOTYPING (DESIGNING, PROTOTYPING, TESTING, VALIDATING AND ITERATING)

The validation matrix is a combination of designing, prototyping (in smaller scale), testing, validating and iterating. Design: With DFMA as a design input, transformable connections of different principles will be designed. It is vital that at this stage to focus on the principle of the transformable connection and its function rather than feeding off existing solutions. The different transformable connections will function uniquely therefore a variety of different options will become available when testing and comparing for the final selection.

Prototyping: These components will then be prototyped using FDM with recycled PET to mimic the properties of an object printed by a Comau Robot. The rapid prototypes will mostly be of smaller scale unless a 1:1 scale prototype is necessary. Prototyping will allow for the components to be tested true to its material and manufacturing method. Adapting a design- build approach, quick changes can be made then prototyped and tested. It is also viable to prototype using other means if required to test different criteria.

Testing: Once prototypes are printed the structural and material properties will either be tested by hand when permitted or by machine to obtain accurate numerical data that will be compared in the validation matrix.

Validation: Criteria will be set in the table shown below (Table 4) according to the relative importance guided by weighting criteria according to the score matrix (Table

Design hinges

Number of different types of joints	Type of Joint			Detail design criteria according to relative importance matrix as above, according to the following expanded criteria (Direction, load bearing capacity, Number of movements required per lifespan, number of possible movements, Minimum bending radius, Maximum bending radius before failure, possibility to expand, Maximum transformable distance, single person handling)
1.	Bending Movement			
	Type A			
	Type B			
2.	Sliding movement			
	Type C	PROTOTYPE JOINTS	TEST JOINTS ACCORDING TO RELATIVE IMPORTANCE OF DESIGN CRITERIA	
	Type D			
3.	Rotatable hinges			Insert findings according to prototype testing
	Type E			
	Type F			
4.	Interlocking			
	Type F			
	Type G			

Table 4: Validation matrix for designed transformable connections to choose optimal transformable connection designs. (Stage 6) (Own illustration)

3). Once numerical data is entered, the best possible outcome/ result of the tests will be detected depending on which transformable connection has better properties and higher score compared to the others. If one or more transformable connections have met an above average score for criteria, they will be used for combining with surfaces. A more detailed table of the validation matrix is shown below. This validation matrix takes into consideration the designing, prototyping, testing and validation according to relative importance of the criteria set out at the start of the process.

Different units of measurements will be adapted according to the different set criteria. Any new criteria that would be identified from the designing, prototyping and testing process will be carefully considered and included if necessary.

Once designed, prototyped, tested, validated and iterated according to prioritize criteria, they can be set to combine with the surfaces designed in the embodiment design phase.
The above validation matrix specific to the design task will be used multiple times in the design, prototyping, testing, validation and selection of the transformable connection + surface design phase and to validate the final iteration which will be printed using the Comau robot arm.

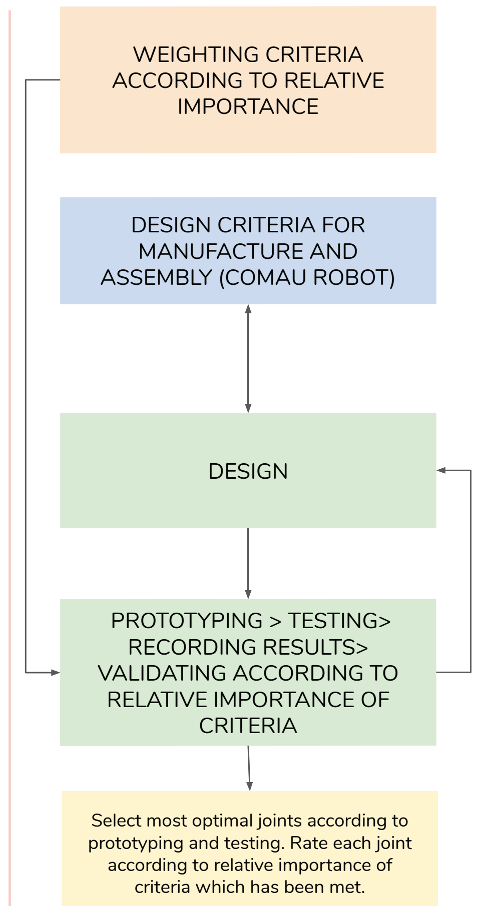


Image 6: Complete design by research and prototyping cycle for a single component (Stage 4, 5 and 6 combined) (Own illustration)

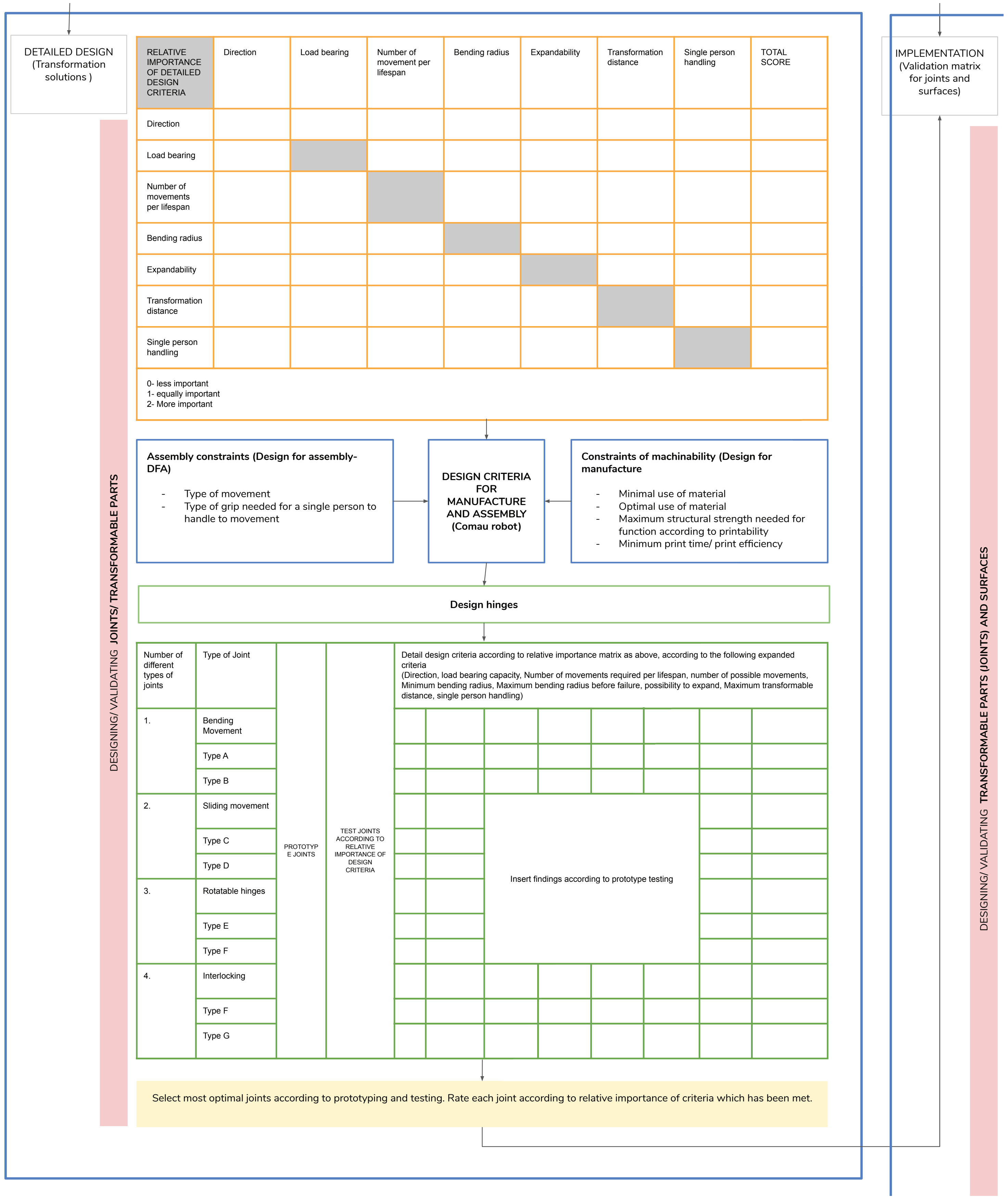


Image 7: Complete design by research and prototyping cycle in detail for the 'combination' phase (Stage 4, 5 and 6 combined) (Own illustration)

5.3.1 ADAPTATION

Due to the nature of the design task, Validation of the prototyping had to occur in two sections of the methodology;

1. Detailed design
2. Combination design.

The specifications for detailed design can be considered quite different to the specifications of combination design since the transformable connections will be considered the modular element while the components designed for combination design can change or be adapted according to different designers and their specific needs.

DETAILED DESIGN

The detail design phase evolved into methodology process as seen in the diagram on the right.

Similar to the initially proposed sequence for weighting and validating, the adapted methodology follows the same process.

A. WEIGHTING CRITERIA FOR DESIGN

The weighting of the criteria were different for both the detail design and combination design in terms of the criteria listed for each part of the design. Other than the differences in criteria, The weighting criteria for detailed design can be seen in the diagram below;

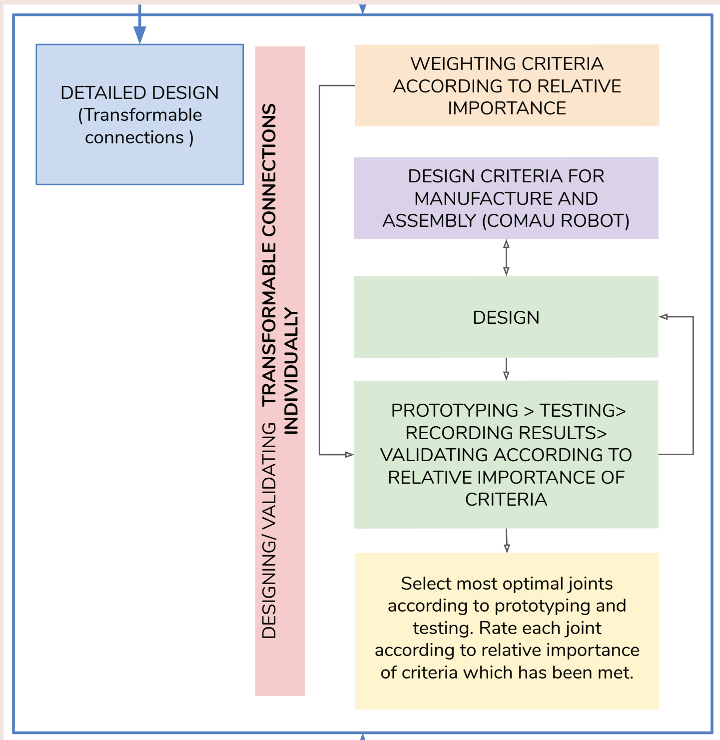


Image: Complete design by research and prototyping cycle for the detailed design phase (Own illustration)

Primary criteria (Vertical) will be weighted against the criteria to be considered (Horizontal) and compared against each other. A grading system was then implemented as follows;

0= Less important (vertical against horizontal)

1=equally important (vertical against horizontal)

2=More important (vertical against horizontal)

	RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA	Possibility to move in single direction when transforming	Load bearing of transformable connections	Maximum movement until failure	max number of movements per lifespan	Bending radius	Expandability	Transformation distance	Single person handling	TOTAL SCORE
	FOR TRANSFORMABLE CONNECTIONS	To be considered against								
Primary criteria considered	Possibility to move in single direction when transforming									
	Load bearing of transformable connections									
	Maximum movement until failure									
	max number of movements per lifespan									
	Bending radius									
	Expandability (for the hinge itself to expand as per design)									
	Transformation distance									
	Single person handling									
	0- less important 1- equally important 2- More important									

Image: Detailed weighting criteria for the detailed design phase (own illustration)

Accordingly, the criteria that had a score of 5 and above were taken into consideration when further designing the details. Any criteria below a score of 5 were not taken into consideration due to the criteria weighted more than a 5 outweighed the necessity for any more criteria with less weighting or were deemed irrelevant for the design of the particular detail itself.

B. DESIGN CRITERIA FOR ADDITIVE MANUFACTURING

It was important that all designing of any detail or component needed to be heavily influenced by the manufacturing process; Additive manufacturing. Due to the nature of the printers very specific measures needed to be considered and the design adapted according to the limitations of the printer. Some of these measures are specific to;

1.
2. Base chamfering
3. Embossing and engraving
4. Overhangs
5. Unsupported holes
6. Wall thicknesses
7. Pins
8. Feature sizing
9. Base corners
10. Bridging
11. Filleting edges
12. Modeling threads
13. Clearances
14. Hole sizing
15. Unsupported edges

Further detail and illustrations can be found under Detailed design> Design criteria for Additive manufacturing and designing p67

C. DESIGNING AND PROTOTYPING

Once the weighted criteria and constraints for additive manufacturing are considered, the details can then be designed accordingly. Once designed these transformable connections will be prototyped using a Delta Additive manufacturing printer with recycled PET filament used as the printing material. Recycled PET filament will be used for all prototypes to simulate the same material properties as if the product would be printed 1:1.

D. TESTING AND VALIDATING

Once prototyped, the details were tested on a basic functional level to see if it can do the basic movements it's meant to perform. The details were then validated according to a similar process as suggested. However, it was important to find a similarity within weighing and validating of the details. Therefore a grading system similar to that of the weighting criteria is adapted for the validation of the details.
Each individual detail will be assessed in the validation matrix according to the grading system specific to each type of detail system (Sliding system, Folding system, Clip system, Hanging system). Once tested and validated, details which have been deemed most suitable will be used to design an integrated design of transformable connections with functional surfaces in the next stage.

GRADING SYSTEM		Sliding	Folding	Clip	Hanging
	Single	0	2	-	-
	Double	0	2	-	-
	Multiple	0	1	-	-
Direction	*None*	2	0	-	-
	Yes	2	-	2	2
Load bearing Capacity	No	1	-	0	0
	>90' - no	0	0	2	0
	<90 - yes	0	2	0	0
Minimum bending degree	none	2	0	2	2
	Yes	0	2	-	-
Expandability	No	2	0	-	-
	Yes	2	2	2	2
Single person handling	No	0	0	0	0
	Yes	2	2	-	-
Duplicate as surface	No	0	0	-	-
	Easy	-	2	-	2
Ease of handling	Medium	-	1	-	0
	Yes	2	2	2	2
Sucess after prototyping	No	0	0	0	0
	Yes	2	2	2	2
Success after testing	No	0	0	0	0
	Partially	1	1	1	1

Table: Grading system for each individual system for cohesion (Own illustration)

Type/name			Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	**Success after prototyping**	**Success after testing**	**Total**
Name of system												
Profile 1												0
Profile 2	PROTOTYPE JOINTS											0

Table: Grading system for each individual system for cohesion (Own illustration)

COMBINATION DESIGN

The weighting of criteria remained the same method as per for the detail design. The only difference being, the specific criteria that each unique component needed to entail in order to fulfill its specific function. Therefore the methodology for weighting criteria remains the same.

Design criteria for Additive manufacturing remains the same. Further details and illustration under Detailed design> Design criteria for Additive manufacturing and designing p67.

Manufacturing method for testing remains the same. All prototypes will be printed on a smaller scale for the purpose of validating the designs. The validation of the components will be done in accordance to the same grading system of methodology implemented for the detailed design phase. Following is a diagram adapted to the combination design part of the designing process itself;

Although the methodology remains the same, the criteria used for validation differs as the designs contain transformable connections and functional surfaces. No selection will be made, however each different component will be assessed on if it fulfills basic requirements for its specific function.

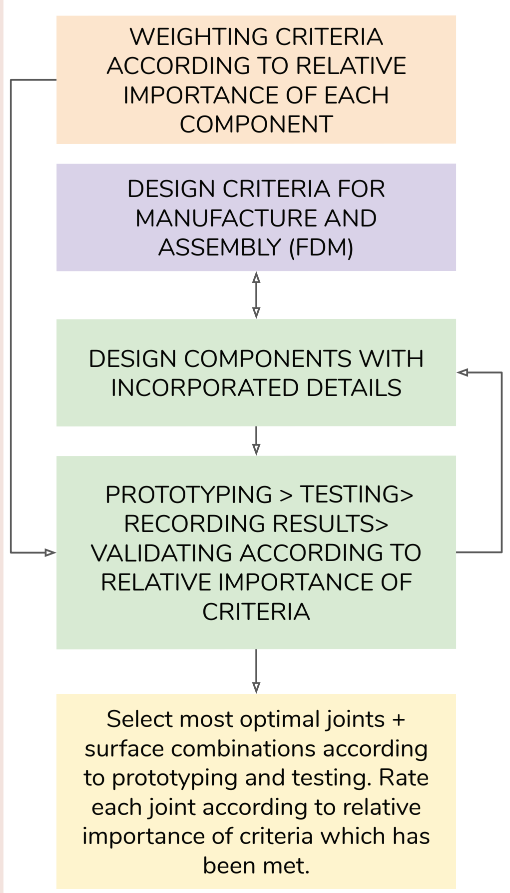


Image: Complete design by research and prototyping cycle for the combination design phase (Own illustration)

Type/name	Discription	Combination of transformable connections used	Do the TC's complement the possible fucntion	Can the component perform more than one function	Can the componnt bare weight	Is it possible to adapt the component for a different functi	Ease of handling	Single person handling	**Success after prototyping**	**Success after testir**	**Total**
Component 1											0
Component 2											0
Component 3		PROTOTYPE JOINTS									0
Component 4											0
Component 5											0
Component 6											0

Image: Verification chart for combination design (Own illustration)

	Yes	No
Ease of handling	2	0

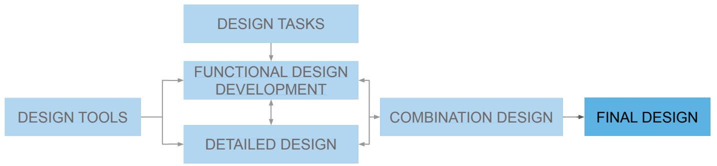
	Yes	No
Single person handling	2	0

	Yes	No
Success after Prototyping	2	1

	Yes	No
Success after testing	2	1

Image: Grading system for verification chart of combination design (Own illustration)

5.4 FINAL DESIGN VALIDATION (VALIDATION PROTOTYPE)



The above mentioned design by research and prototyping cycle will be implemented in the 3rd phase of the design methodology for validation;

1.
2. Detailed design phase (designing transformable connections)
3. Combination design phase (combining transformable connections with surfaces designed in the embodiment design phase
4. Final iteration phase (the chosen iteration will be optimized for Comau robotic arm print)

Once all three phases have been designed, prototyped, tested, validated and iterated when necessary, the final iteration will be used to print the 1:1 validation prototype. A list of design goals to achieve with the 1:1 validation model is explained under 'Design goals for validation model' below.

1:1 FDM VALIDATION PROTOTYPE USING COMAU ROBOTIC ARM

By this stage, certain tests will have been conducted and validated using the Comau Robotic arm. During the design and prototyping stages, machinability will be taken into consideration. Once the final iteration is chosen for print, further optimization will be done according to the criteria set out for validating the 1:1 validation prototype. Similar to the design phases of detailed design and combination design, each criteria will be weighted, design optimised according to manufacturing process and tested to validate according to relative importance of the criteria.

Definitive design criteria have not been set for the validation prototype. Reasoning for this is because there will be many changes to criteria along the way when prototyping on a smaller scale. According to the knowledge on material and the production process, criteria for validating the validation model will be set out accordingly further on into the validation methodology.

DESIGN GOALS FOR VALIDATION MODEL

Although design criteria for the validation model have not been set, a fe design goals to be achieved by the final validation model are as follows;

1. The final validation model validates the use and process implemented in the methodology
2. Design ideas set out for 'transformable multi-functional interiors for mono-material printing using recycled PET' have been achieved
3. The design process was functional and applicable
4. Functionality of the design including the functionality of the individual transformable connections were met according to criteria
5. The use of prototyping as a design research method is justified by the overall validation model.

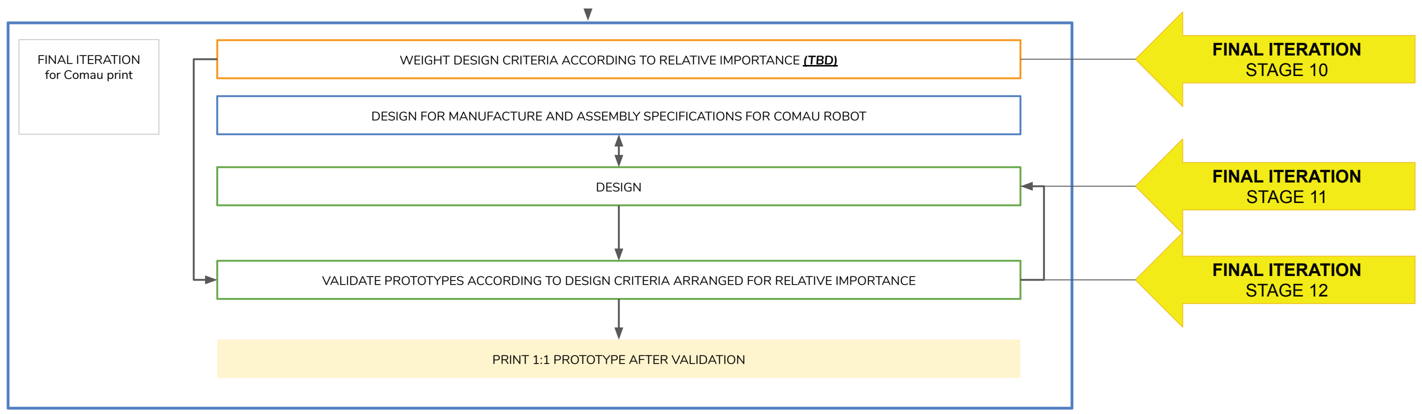


Image : Complete design by research and prototyping cycle for final iteration (Stage 4, 5 and 6 combined) (Own illustration)

ADAPTATION

The possibility to design a 1:1 model was eliminated by the shutting down of university facilities due to the Corona Virus outbreak. Therefore, due to the lack of possibility to print a 1:1 prototype using the Comau robotic arm, a scaled model, a larger sized model will be printed for testing purposes. Due to this limitation there will be no use further for the FDM validation using the comau robotic arm.

Instead, the same settings/ design process used for the Delta printer will be used for the larger scale model.

SUMMARY

The initial methodology suggested during the early stages of this thesis continued to enhance the directed design process for this thesis in general. Although a few changes according to the hands on design process were made, they still kept to the essence of the methodology suggested from the start. All changes have been recorded and justified by reasoning. The methodology for this thesis having been a main part of the design process, will continue to drive the direction of this thesis cohesively.

This methodology is of course open to interpretation within other design tasks specific to Additive manufacturing. However, the methodology can also be used for design tasks to other manufacturing methods that may allow it.

Detailed version of the older methodolgoy can be found in Appendix II

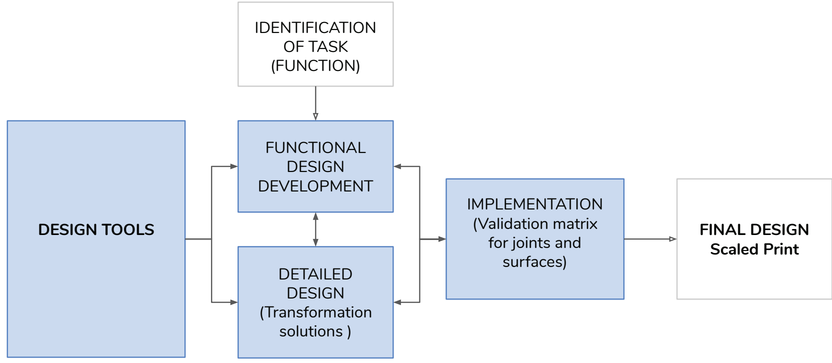


Image : Adapted methodology summarized (Own illustration)

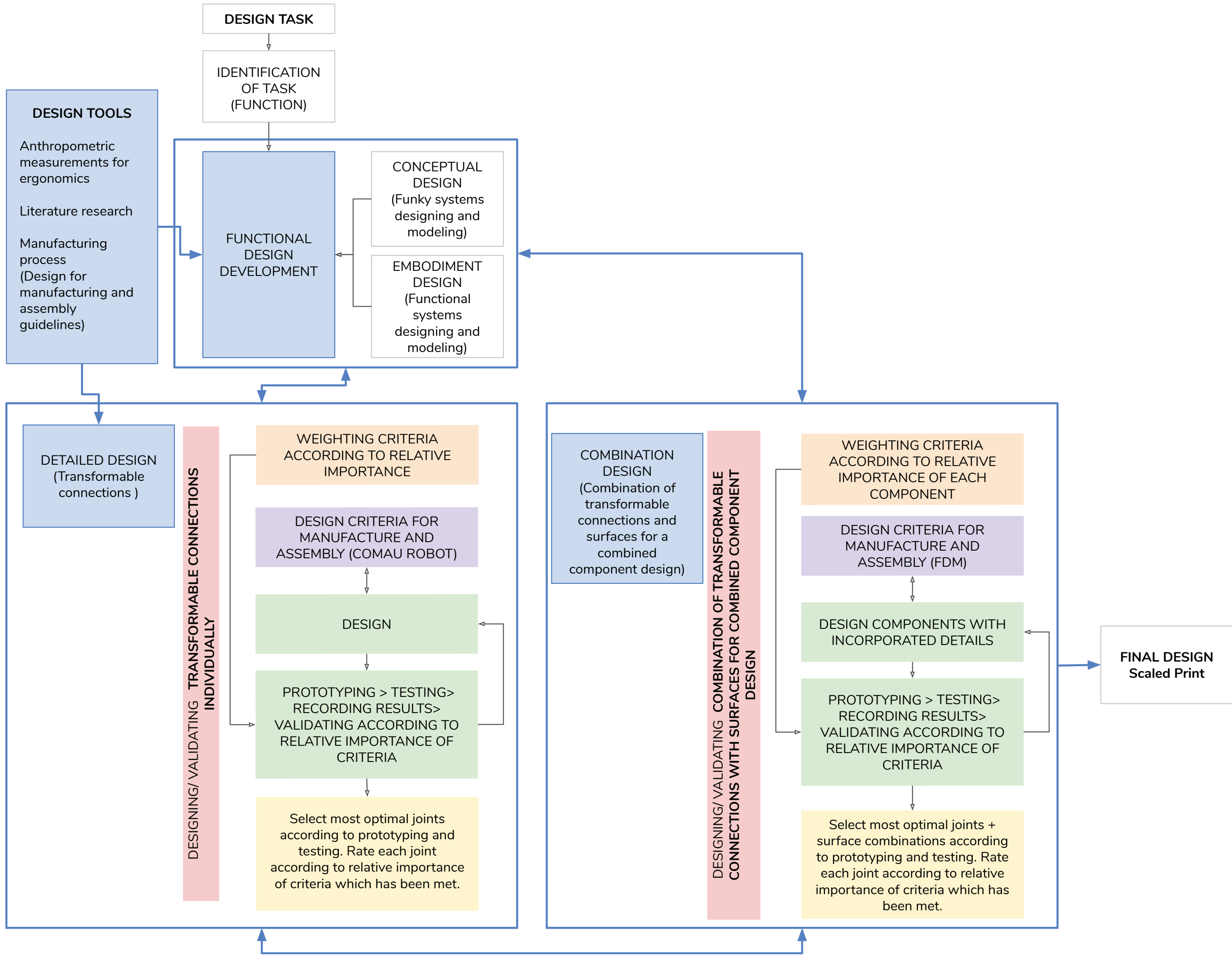
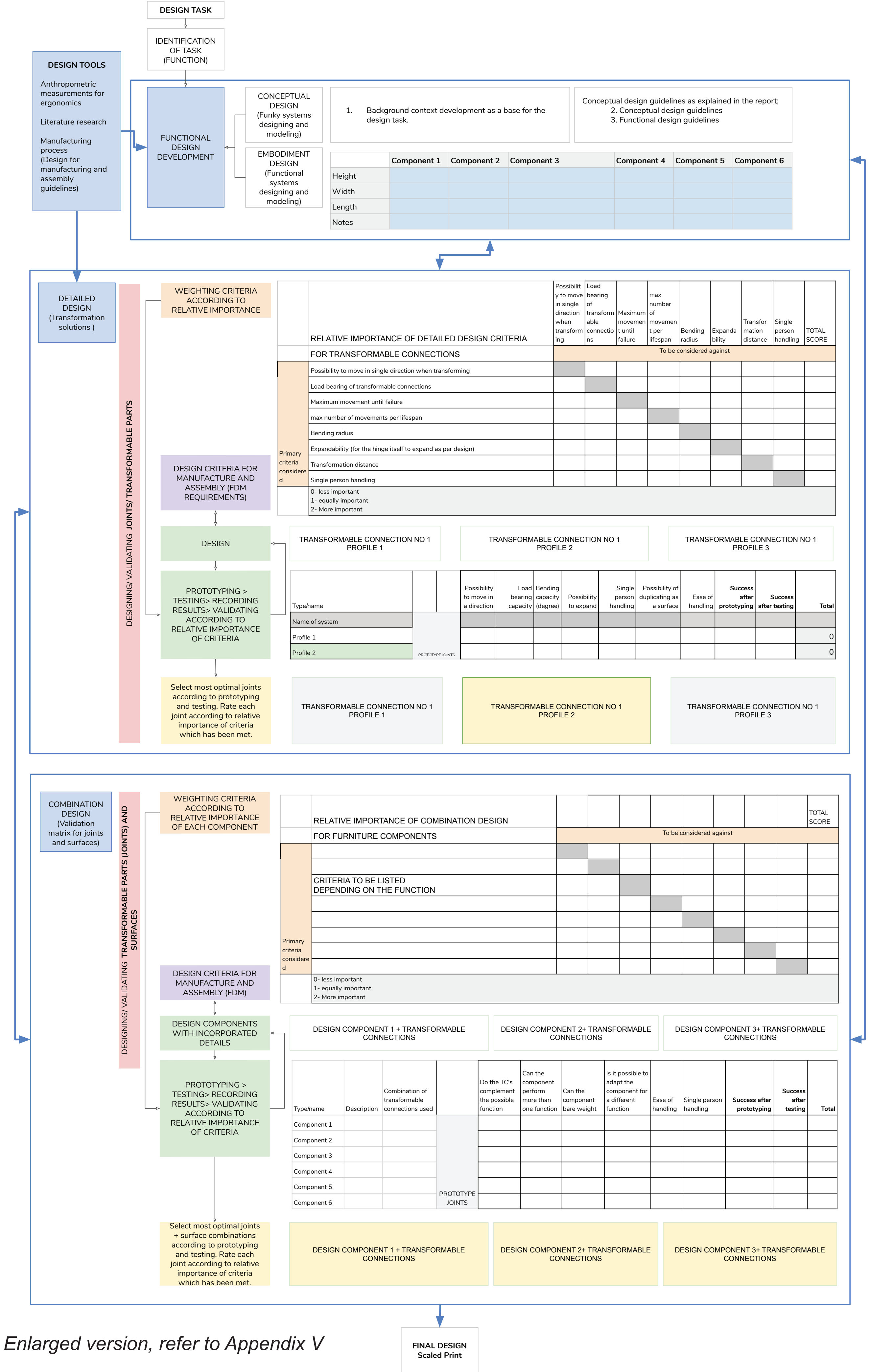


Image : Adapted methodology descriptive (Own illustration)



Enlarged version, refer to Appendix V

Image : Adapted methodology in detail (Own illustration)

6. DESIGN BY RESEARCH: DESIGN TASK

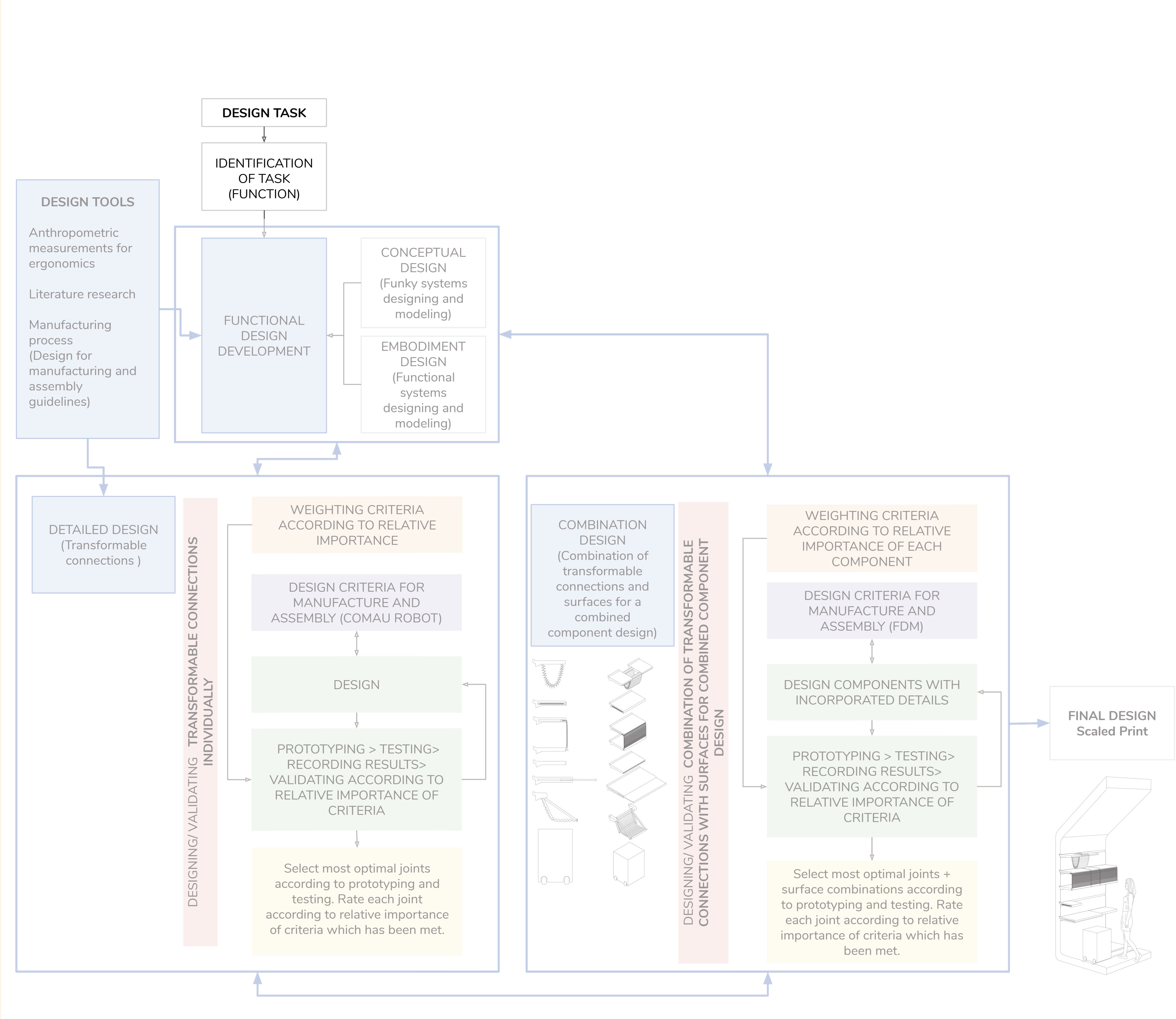


Image: Adapted methodology (own illustration)

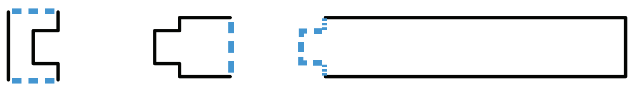
DESIGN BY RESEARCH

6.1 DESIGN TASK

With the aim of giving recycled PET an improved purpose, the material will be digitally designed interior components and rationalized for the additive manufacturing process. As an extreme example of the possibilities of FDM using recycled PET, a single module of a modular tiny home focusing on a modular customizable system of interior components will be designed in a few design tools (further explained in the Methodology section). A standardized flexible connection system, optimized and tested for FDM will be designed and shown by exemplary iteration of interior modules. The standardized transformable connection system allows design freedom for who ever incorporates a modular component system for any project here onwards. The standardized transformable connection system hopes to take advantage of the open source nature of FDM prototypes readily available on many on-line platforms like thingiverse.com to allow a designer to adapt these tested transformable connections into their design.

The design task will be carried on and validated using the following steps (more detailed descriptions provided in the Methodology section);

1. Literature research
2. Research by design (Using prototyping as proof of concept)
3. Validation matrix using prototyping (Designing, prototyping, Testing, Validating and iterating)
4. The final transformable connections chosen and combined together into one exemplary design.



Module Transformable connection Component

Illustration: Scheme of three sections of the design (Own Illustration)

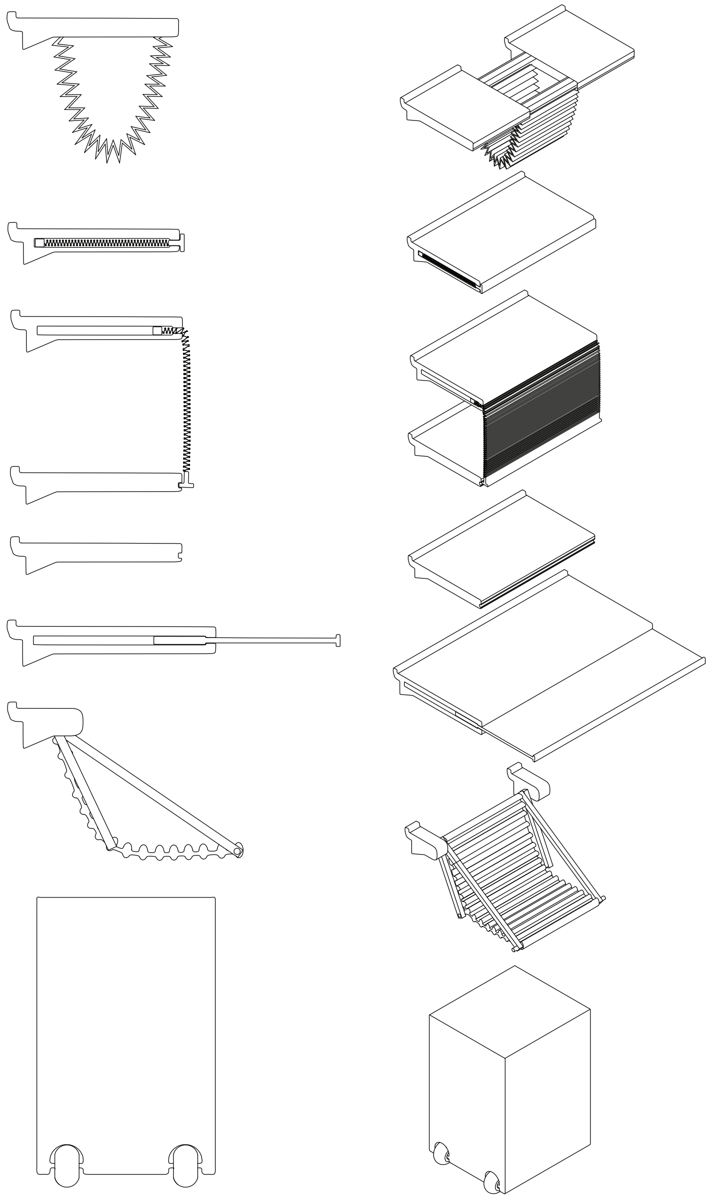


Illustration: section and perspective of designed transformable furniture components (Own Illustration)

6.2 DESIGN REQUIREMENTS BASED ON THE DESIGN TASK

The following design requirements refer to the design task. The following are two possible paths for exploring the concept of transformable connections.

Designing a standardized system of connections for a adaptable modular living system (Focus on the transformable connections with an exemplary design to follow)
Designing furniture components for optimized printing process incorporating the transformable connections (Fixed connections and components designed together for optimal printing.)

A descriptive listing of the design task broken down with possible pros and cons needed to be debated in order to decide on a specific direction of design. Therefore the following table lists out what could come out of each direction to aid the success of this design task.

Transformable connection system for adaptable design:

- With a main focus on transformable connections, more verification and justification can be done in this particular aspect of the design itself.
- With having a standardized framework for the transformable connections, the extension of surfaces are open to interpretation according to different designers and their needs at any given period of time.
- The transformable connections can be published on the web on sites such as thingverse.com for easy access and adaptation by different designers.

Fixed system with transformable connections combined with surfaces for functional purposes:

- The surfaces to be finalized and designed for optimized print along with the transformable connections.
- No differentiation between the transformable connections and the extended surfaces.
- Components will be designed for optimized print which will eliminate the possibility of customization.
- If not used in the exact same context as this thesis is based on, the components will be of little practical use once printed.
- Having designed components as a whole eliminates the need for further development of this topic, unless seen necessary.

Illustration: Scheme of Transformable connection system for adaptable design. (Own Illustration)

Illustration: Scheme of fixed system with transformable connections combined with surfaces for functional purposes (Own Illustration)

SUMMARY

According to the above listing of pros and cons, a **transformable connection system for adaptable design was chosen to be further developed**. This choice was purely due to the possibility of giving other designers freedom of interpretation and the tools to design components for their own living module. Given the nature of AM and the nature of open source availability of extensive digitally manufactured models for printing, it was only suitable this project added to this mass platform of knowledge.

Therefore the modular transformable connections, the universal hanging system for the living module wall, the design grid (as a design parameter) and an exemplary design and the validation methodology will be the main outputs of this design task.

6.3 BACKGROUND CONTEXT

WHY A TINY HOME?

A tiny home will be used as the context for the further development of this design task. A tiny home is used as an extreme example of living amidst all the plastic consumed by individuals. It is meant to be a conceptual representation of the excessive use of plastic in our day to day lives and the lack of acknowledgment on how unsustainable this heavy consumption really is.

3 tiny home case studies from within the Netherlands were observed and studied in order to identify necessary specifications for a regulated tiny home. The goal of this study is to identify regulatory measurements for a tiny home in the Netherlands, existing systems of transformable furniture (if any) and to explore ways of designing a tiny home in a more optimal manner.

CASE STUDY 2: MARJOLEIN JONKER, ALKAMAR

Designed by: Buro Walden: Lena and Laurens van der Wal and Vincent hoFTE
Build: Dimka Wentzel
Residence temporary or permanent: Temporary permit until March 2023
Dimensions: 660 x 225 x 400 cm
Foundation: Vlemmix Tiny home trailer
Connections: Off-grid water, electricity, gas, wastewater treatment
(Above information based on tinyhousenederland.nl)

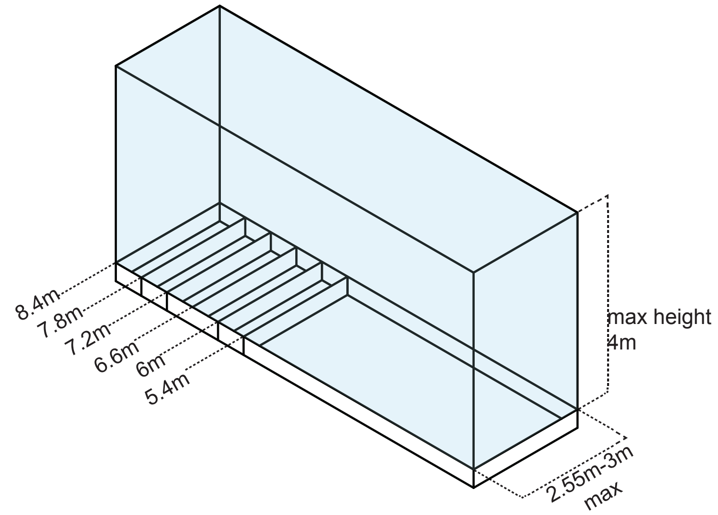
CASE STUDY 1: JAN- WILLEM AND NOORTJE, DRONTEN (SINCE JUNE 2019)

Designed by: Jan-Willem
Build: Self build
Residence temporary or permanent: Temporary permit for 3 years
Dimensions: 720x 255 x 375 cm
Construction material: Timber frame construction with flax insulation and wood facade cladding preserved with 'shou sugi ban' method.
Connections: completely off grid
(Above information based on tinyhousenederland.nl)

CASE STUDY 3: BRAM AND MELANIE VERHEIJEN, WINSSEN

Designed by: Self designed, construction techicality checked by Dimka Wentzel
Build: Dimka Wentzel
Residence temporary or permanent: Temporary permit until March 2023
Dimensions: 720 X 255 X 400 cm
Construction material used: Red cedar wood used on the outside, bamboo finish on the inside, PVC floor, the skeleton of the house is of normal construction wood
Foundation: Three-axel trailer
Connections: connections to power, water supply and gray water drainage
(Above information based on tinyhousenederland.nl)

Furthermore, information with regards to the base of a tiny home, if needed to be transported were taken into consideration according to information stated by Dimka Wentzel on his website Tiny-homes.nl as follows;



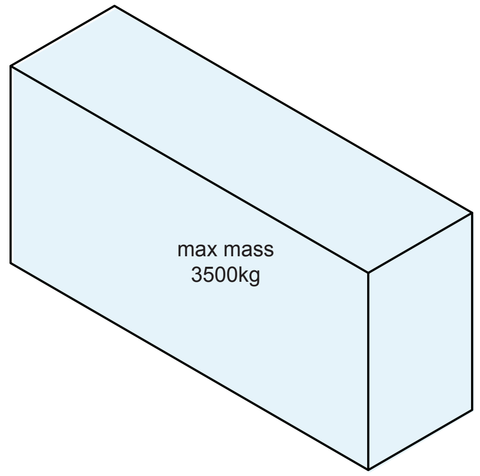


Illustration: Regulations as derived from tiny-homes.nl (Own Illustration)

SUMMARY

According to the above case studies, regulatory measurements, basic design principles of existing tiny homes and inspiration were taken as conclusions. The exemplary tiny home which will be designed as context for this project will mostly be based on similar measurements, however, taking modularity into account. Although the above tiny homes are used as examples, it is important to have FDM and the material qualities of PET consistent as a design input when designing any detail or component of this design task.

POSSIBILITY TO INNOVATE THE CONCEPT OF A TRADITIONAL TINY HOME.

As seen in the tiny home examples used for this project, it is evident that tiny homes although consume less energy, capital for building and man power (Boomgaard, 2018), they still are constructed under the same mindset of regular houses. A traditional construction mindset is evident in the material usage, layout of functions and the minimal adaptability of many of the functions. Although there may be storage under the chairs and a fold-able table, Most of the material used for these constructions are not very energy friendly.

The following are some factors for tiny homes around the world that could use more thought and innovation;

1. Inefficient use of space: Most tiny homes still have designated areas for living, eating, sleeping etc.
2. Tiny homes as shown in the case studies above are based on similar principles to a larger scaled house. I.e. having different rooms/ areas for different functions
3. Tiny homes based on the case studies are made of timber, steel aluminum and are less sustainable in the long run compared to the recyclability and re-usability of material such as recycled PET.
4. There is a tendency for materials such as steel to be of higher price point comparative to material such as recycled PET.
5. Building that involves human intervention could possibly lead to more human error compared to a programmed robot based on precision, time specifications, accuracy and efficiency. (Pereira et.al 2019)

It is possible that this project explores ways in which the concept of a tiny home can be explored in different ways they can be designed and different methods fo manufacturing that can be adapted. Further exploration into manufacturing methods and material use may allow for potentially more sustainable and inexpensive designs. As solutions, the following conceptual ideas will be incorporated as design guidelines for the design assignment;

1. Design modules in a way that they can be adapted to more than just one function. Possibility to design adaptable living modules with the ability to be customized according to different functions at different times of the day.
2. Design based on principles not governed by larger scaled homes i.e. having different rooms/ spaces for different functions rather than adaptable spaces. This could be achieved by looking at the tiny home and its functions rather than as a smaller house.
3. Using recycled PET as a building material will give the user ownership over base material which can be recycled over multiple times in order to redesign and reprint anything new based on the need at a certain point.

Image: 3D printed micro home Amsterdam, DUS architects

CONTEXT FOR PROJECT DEVELOPMENT

The following tiny home was designed according to regulations as per the above case studies of the 3 tiny homes.
The following design is considered to be ONLY the background/context for which the rest of the project will then build on. It is designed to give a background to the specifics of this thesis topic. Therefore no further studies will be done on the design of the entirety of the tiny home.

The measurements are specified to be of a modular design . The 1.5m x 1.5m modules will connect to other modules of the same tiny house series according to the needs of the client and the necessary functions.

1.5m x 1.5 m modules were decided based on 3m of maximum width a tiny home can have according to regulations listed on Tiny-homes.nl. A 3m grid can allow for an even split of 1.5 m modules. The major restriction for a tiny home being the width and height (for road transportation), the 3m maximum width is taken as a base measurement for all further dimensions of the context tiny home. As the length is an adaptable variable, it is possible to keep adding 1.5m x 1.5m modules to extend the length of the tiny home as a whole. Once parked or built on a permanent plot, the tiny home can keep extending using 1.5m x 1.5m modules both in length and width as seen necessary by the user.

Below shows the modular design of the layout for the tiny home. The design allows for modules to attach or detach in order to customize a space according to the user. Starting with a 9m2 the living modules expand according to the amount of users or according to the amount of space required by the user. Following expansions are purely as examples of spaces that can be combined together using the same sized module for different users, according to their needs.

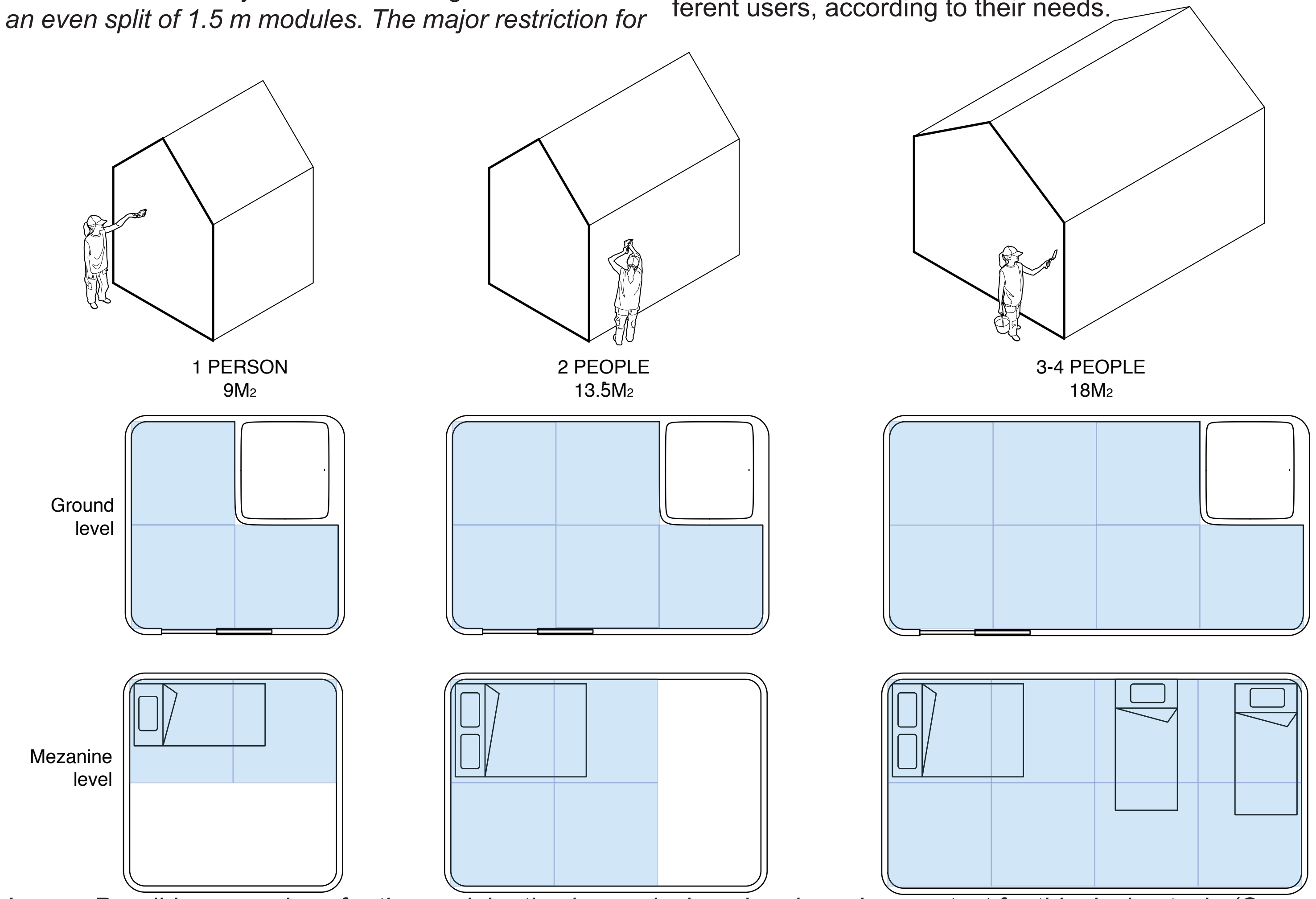


Image: Possible expansions for the modular tiny home designed and used as context for this design task. (Own Illustration)

7. RESEARCH BY DESIGN: FUNCTIONAL DESIGN DEVELOPMENT

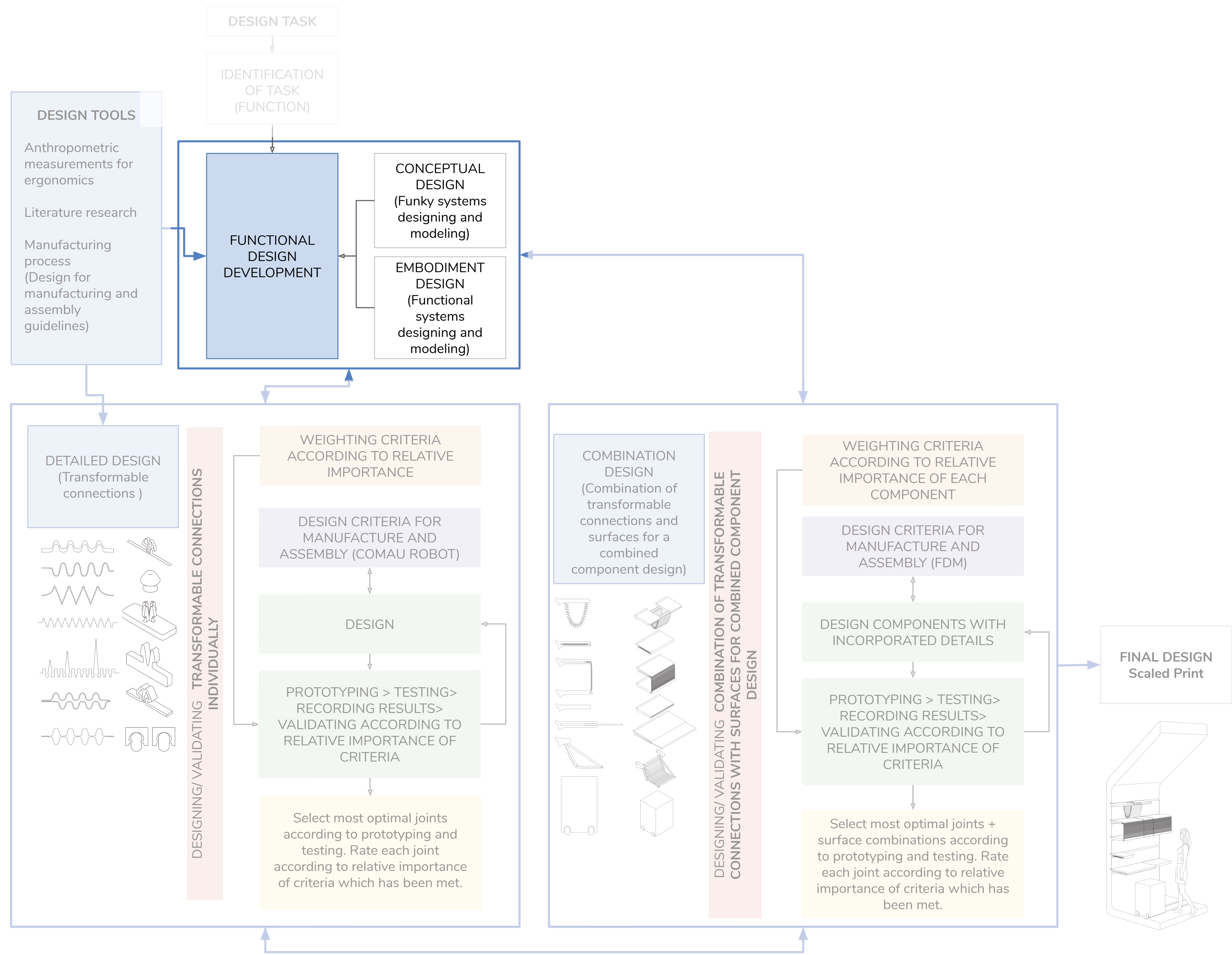


Image: Adapted methodology (own illustration)

7.1 FUNCTIONAL DESIGN DEVELOPMENT

Functional specifications entail the basic measurements required for suggesting a function according to its ergonomic properties. Literature research and Ergonomic measurements were taken as the main design tool for the functional specifications of this design.

Specifications are drawn out from Human Dimensions and Interior Spaces by Panero and Zelnik (1979) and Architects Data by Ernst and Neufert (2000). In order to design the basic geometries of the living module, basic measurements based on living, eating and studying were taken into consideration as follows.

The following sketches show the overlapping of certain functions against one another. Once these overlaps were identified, specific measurements were chosen where one measurement could serve the purpose of multiple functions.

The measurements chosen from the overlapping of functions have been recorded in the above graph for clarity. Further these measurements will be used to design the basic components of the module. The transformable connections and

Ergonomic measurements are used as a key consideration as the base measurement for the designing of the module due to its years of relevance, observation and testing having been done. This sets a solid base for the rest of the design to begin developing both in its conceptual phase and detailed design phase.

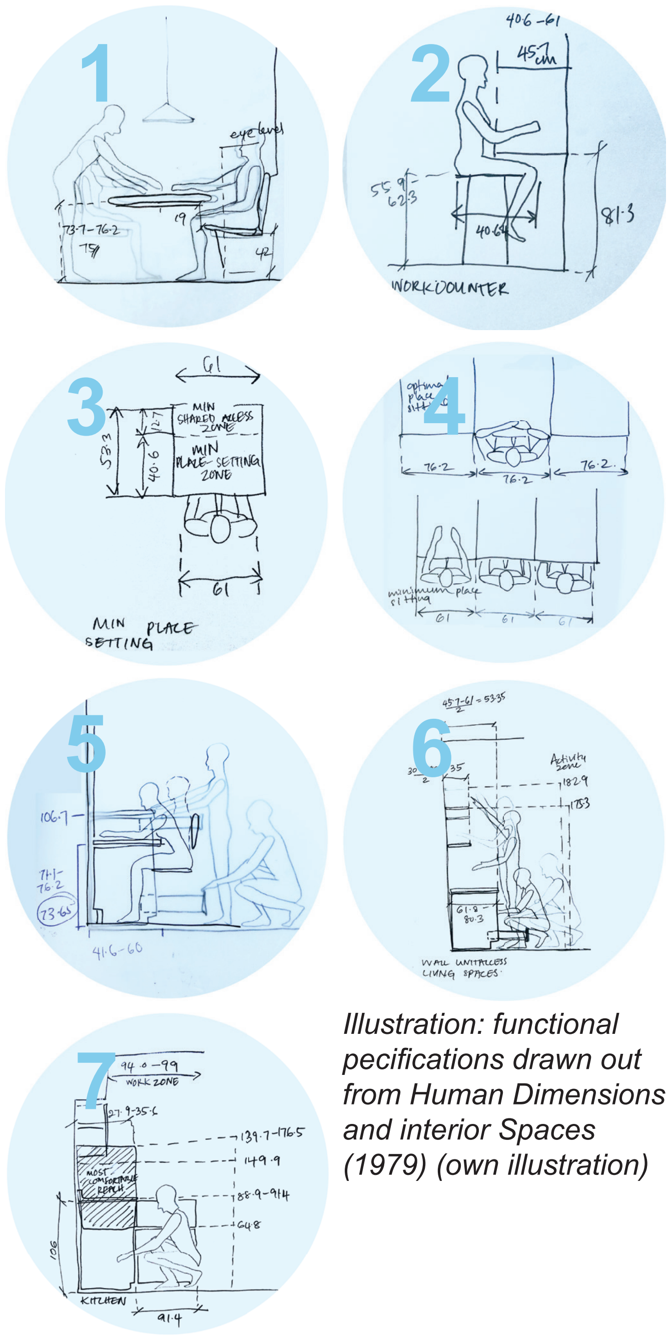


Illustration: functional pecifications drawn out from Human Dimensions and interior Spaces (1979) (own illustration)

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
	Box shelf	*Small shelf*	*Universal component*	*Wide shelf*	*Vertical support*	*Roller box*
Height	35	35	20	45	60	42
Width	35	30	1	6	6	42
Length	35	30	15	90	90	62
Notes	illustration 6	30cm according to wall grid, Ill 6	Universal component is to have holes printed in specific places to allow other components such as televisions and photographs to be mounted on	Illustration 2,3,4,6	Illustration 7	illustration 1,5

Table: inputs as functional criteria derived from Human Dimensions and interior Spaces (1979) (ow illustration)

INTERNAL GRID

The information based on regulations for tiny house measurements, the maximum width of a tiny home needs to be 3m maximum. In order for a tiny home to be handled by a few individuals, the entire tiny house was divided into smaller modules. The modules allow for ease of handling, assembly and if necessary, disassembly. A standardized module of 1.5m (in length) x1.5m (in width) x 4m (floor to ceiling) has been strategically designed based on the equal division of the maximum width possible (3m) and based on the averaged maximum reach of a person being 1.75m (An average reach of a man being 1.72m and an average reach of a woman 1.77 bases on Human dimensions and interior spaces by Panero and Zelnik 1979, page 215). Accordingly the modules were divided as shown below.

Given that smaller interior furniture components are to be designed, for the purpose of modularity and ease of internal space division, the module was further divided into a smaller grid to allow for customization. A small grid of 30cm x 30cm was decided due to;

1. The possibility of having small components. I.e. for parts like lighting fixtures, components that could be used to screw in fixtures for a television etc.
2. The ability to multiply in length 30 cm at a time. Therefore have components that are 30cm, 60cm, 90cm, 120cm and 150cm.
3. To promote minimal space wastage and maximum use of the area of the tiny house.

All furniture components further designed will be in multiples of 30cm. The length may differ according to functional specifications, requirements and number of users.

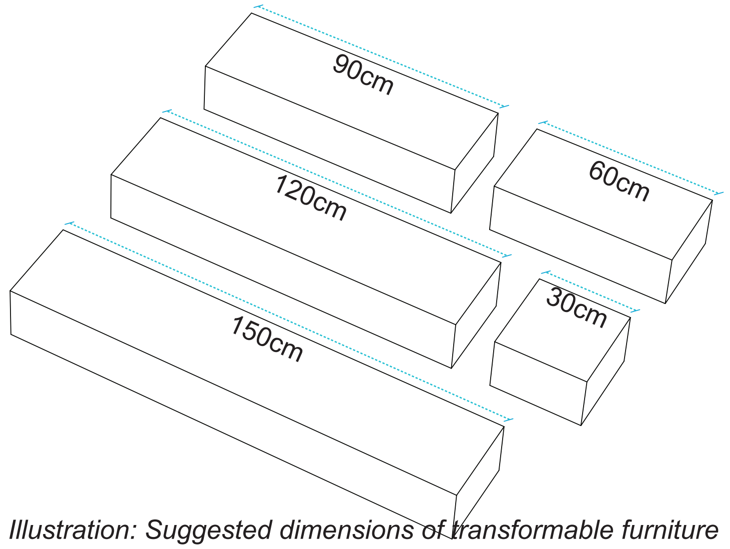


Illustration: Suggested dimensions of transformable furniture components (own illustration)

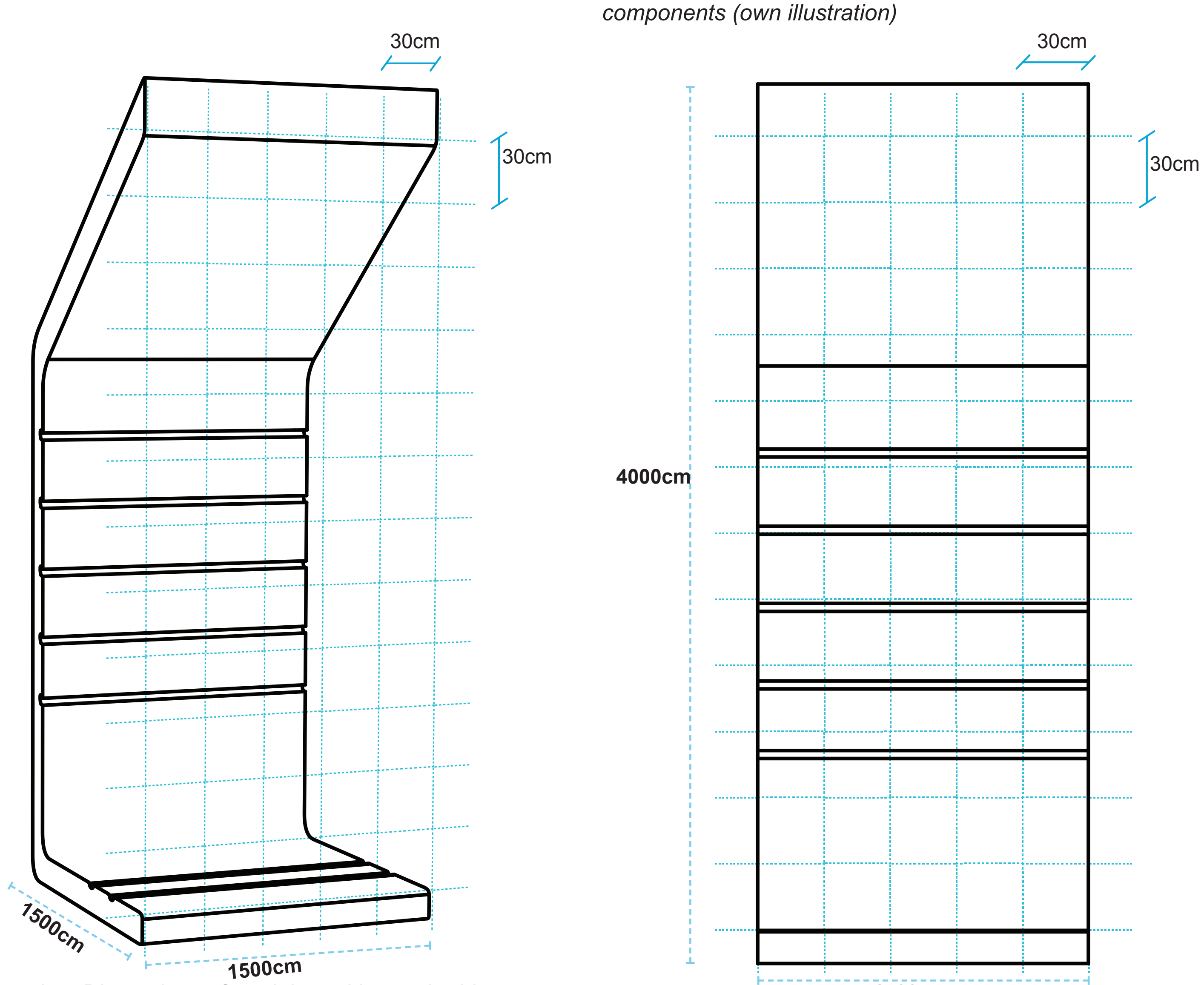


Illustration: Dimensions of module and internal grid

7.2 CONCEPTUAL DESIGN/ EMBODIMENT DESIGN

APPROACH

The main approach to the conceptual design and embodiment design were to use constraints based on function, concept and design requirements as per design task.

DESIGN CONSTRAINTS BASED ON FUNCTIONAL NECESSITY

As a first design input, the conceptual development is based on the functional design specifications. These functional specifications provide certain positive constraints to the conceptual development of the design. ***Functional constraints*** taken forward to influence the conceptual design of this design task are as follows;

1. Specific measurements are required as a minimum for certain functions to take place in a given surface.
2. Different functions have different area requirements
3. Area requirements and measurements for a certain function differ according to the number of people intended to use the space.
4. Different heights for surfaces naturally suggest functions according to human body measurements
5. Different functions would require different surfaces to work on. I.e a worktop needs to have a flat surface
6. Some functions may need extending based on the amount of people using the surface at a given time
7. Some functions may need to be stowed away depending on the frequency of use and or if they need to be displayed.
8. Duration of use of the component/ how many times per specified time it will be used and if the material allows for it.
9. Multiple uses/ adaptability to different functions of the component rather

DESIGN CONSTRAINTS BASED ON THE CONCEPTUAL DEVELOPMENT

Conceptual design constraints to be considered when developing the concept of this design task:

1. A tiny home needs storage given its limited space capacity, therefore incorporating storage into the design.
2. There should be an aesthetic appeal to the designed components
3. Possibility to be cohesive in design by reflecting the modularity of the tiny home modules into the design of the assembly of components.
4. Design constraints due to the printing process i.e direction of material printed can have a strong impact on structural strength

According to the above constraints it was important to refer back to the basis of what needed to be provided for further development from this thesis. The below argumentation justifies the need for a validated and print tested framework of standardized transformable connections with surfaces open to adaptation.

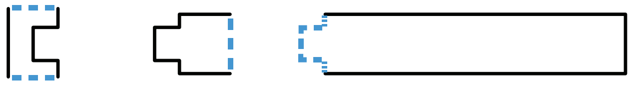


Illustration: Scheme of three sections of the design (Own Illustration)

7.3 INSPIRATION

The following designs were used as possible inspiration to draw from when designing the transformable connections. Although some connections may not be manufactured using additive manufacturing, they could be used as references for similar systems that an be used for designing transformable connections.

Instead of making a mechanical hinge, you can use White Strong & Flexible to make flexible hinges. Here are two example: one using a 'harmonica' structure. In this case the material is about 0.5 mm thick:

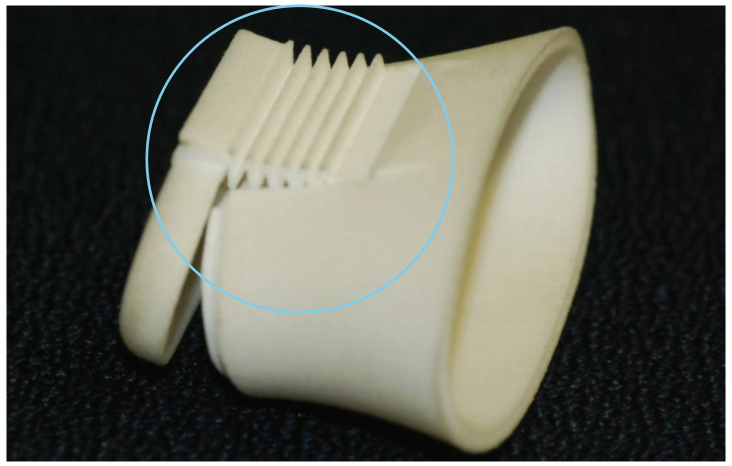


Image: Creating hinges and moving parts
https://www.shapeways.com/blog/archives/141-creating-hinges-and-moving-parts.html

Another approach is to make a long, flat piece of plastic which can bend. The material here is about 0.5 mm thick as well:

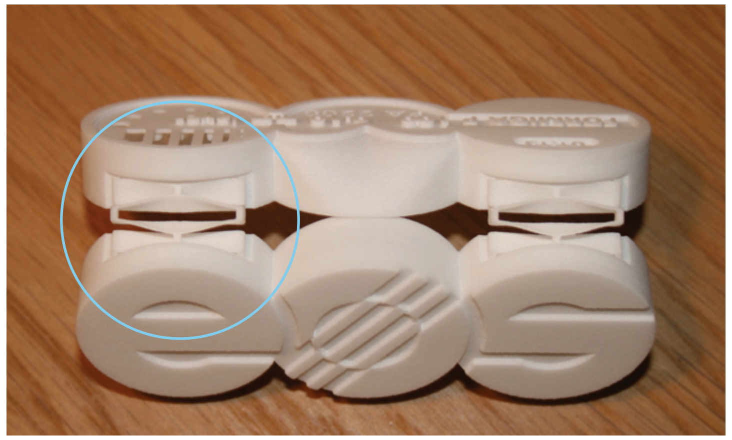


Image: Creating hinges and moving parts
https://www.shapeways.com/blog/archives/141-creating-hinges-and-moving-parts.html

Image: 3D printed glasses
https://nl.pinterest.com/pin/566257353148177436/

Image: 3D Printed belt
https://3dprinted877186161.wordpress.com/2019/04/13/22/

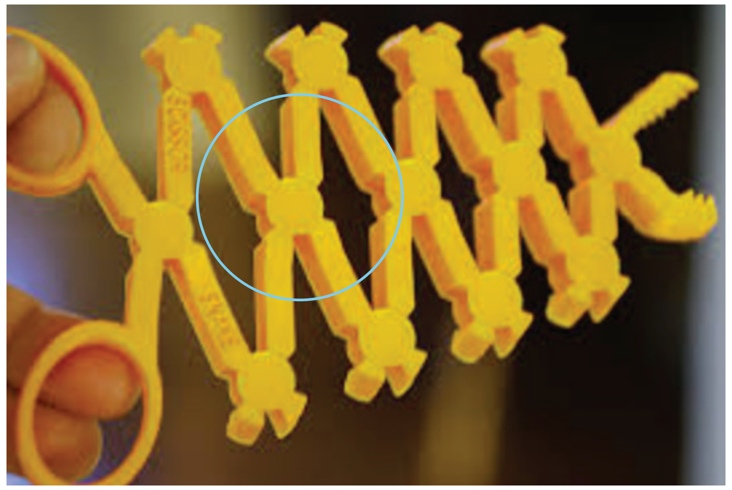


Image: 3D Printed scissor
https://pinshape.com/items/6604-3d-printed-scissor-snake-family

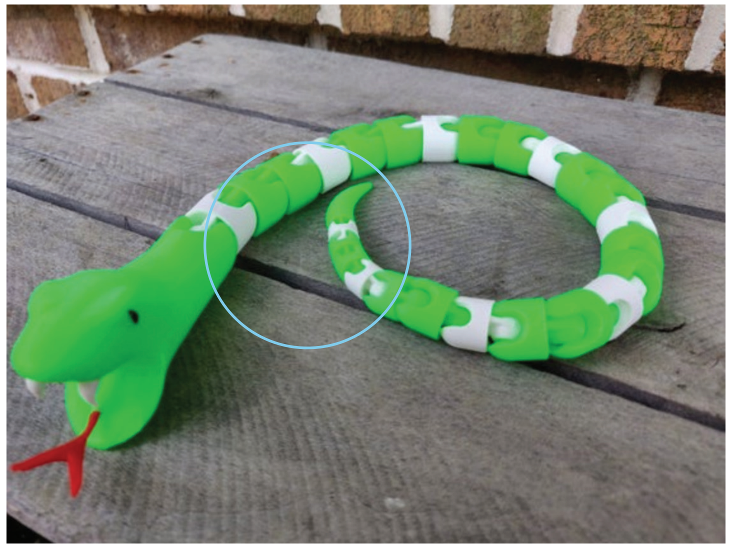


Image: Customizable articulated 3d printed snake
https://www.etsy.com/sg-en/listing/708153809/customizable-articu-lated-3d-printed

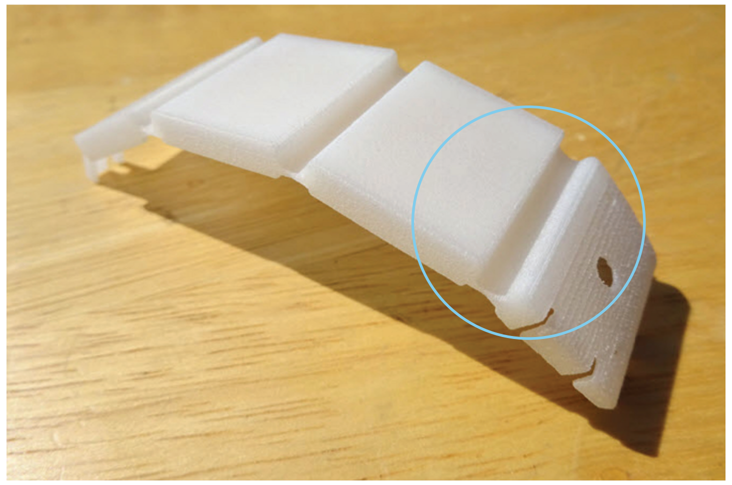


Image: 3D printed living hinge
http://brightpd.com/rapid-low-cost-living-hinges-with-3d-printing/

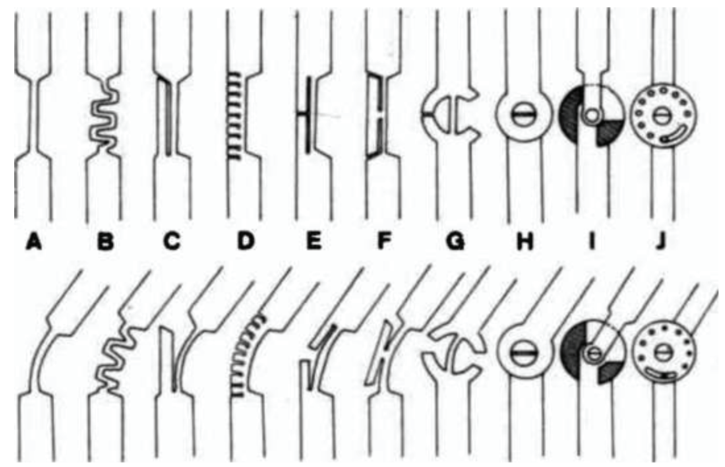


Image: Living hinge diagrams
https://nl.pinterest.com/pin/449093394082229129/

Image: laser cut vector model
https://www.etsy.com/listing/522443707/laser-cut-vector-model-in-stant-download?ref=landingpage_similar_listing_bot-8

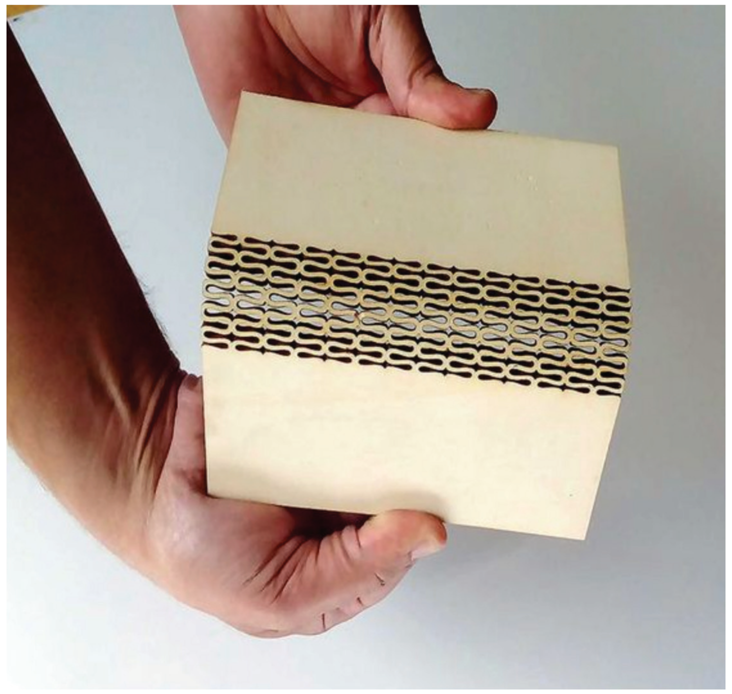


Image: Living hinge template for laser cutting
https://nl.pinterest.com/pin/836895543246443164/

Image: DIY roll out bed
https://www.goodshomedesign.com/build-a-diy-built-in-roll-out-bed/

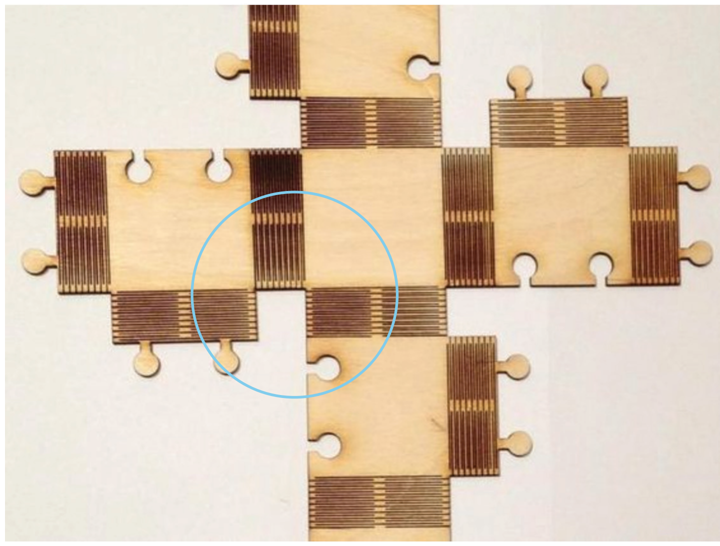


Image: Laser cut table
https://obrary.com/products/laser-cut-cube

The above images have all been chosen to show the basis of how the initial design ideas were developed. Certain images are of 3Dprinted components such as the scissors and the belt whilst some others are of laser cut CLT for bending purposes. Both the materials are solid and come as a single object. Therefore in order to bend or warp this material into a new shape without having to damage the material itself, the material needs to be manipulated and engineered to be able to perform as expected. Therefore it is important to identify the basic system before seeking a solution as every material may have possible unique properties that may suggest a system by its own properties. All the above examples are of living hige systems using a single material.

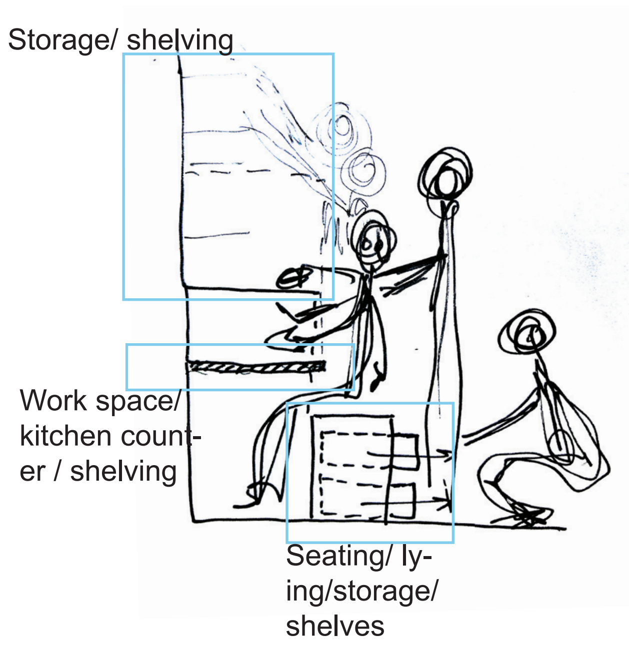
The lever system by pinshape.com for example can be seen as a single print using a single material which uses compression to alter the shape of the object to perform its desired task. The 3D printed glasses and snake show possible bending movements. The laser cut models depict a strong correlation between possible transformable connections for recycled PET due to the method of perforating a surface to create movement. Therefore the above images were used as exemplary/ inspiration for designing transformable, mono material connections using recycled PET.

After carefully considering the context for this project through existing tiny homes, regulatory measurements with a modular approach, specifications for human dimensions drawn out from Human Dimensions and Interior Spaces by Panero and Zelnik (1979), were all used as inputs when designing the transformable furniture. As a design approach, it was inconsistent when trying to design transformable connections without knowing its immediate context; the transformbale furniture.

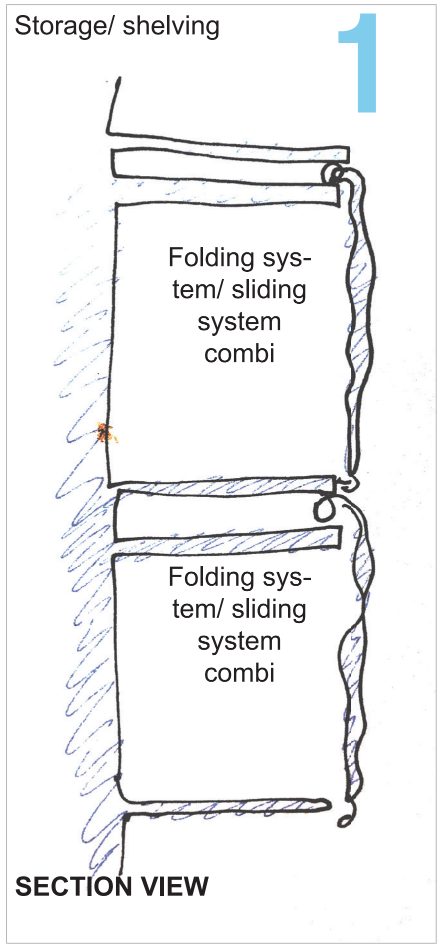
Conceptual sketches were useful int he following ways;

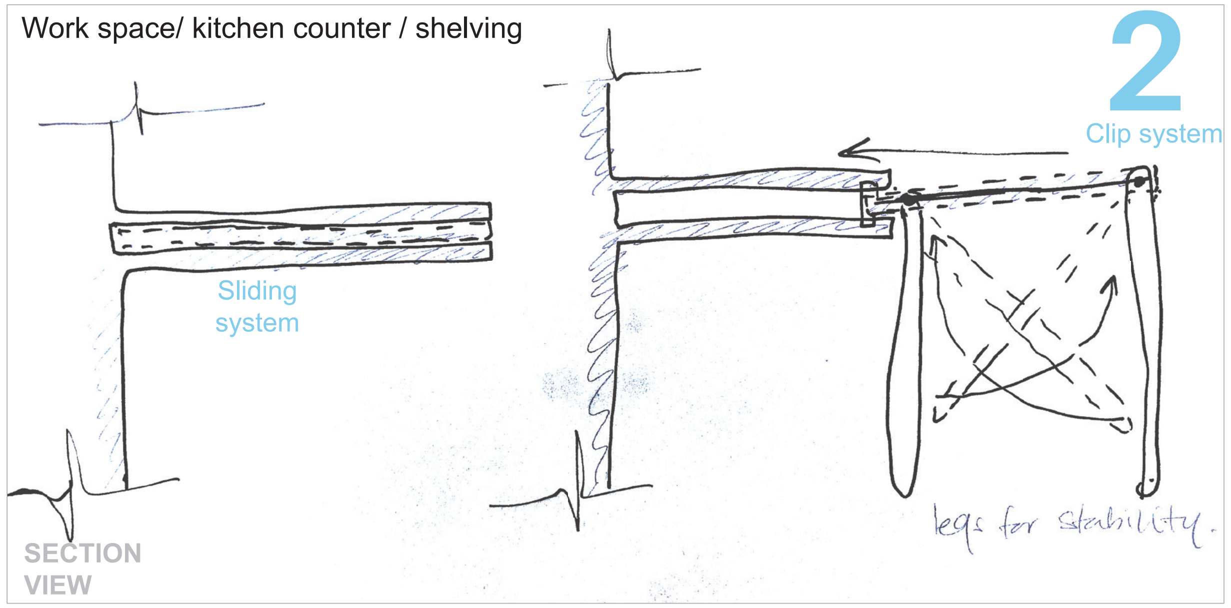
1. When sketching multiple surfaces, it was evident that a few functions were overlapping the same surface, therefore a single surface could be used for more than one function. This further justifies the need for transformable furniture in a space that has a very limited amount of furniture.
2. Many different transformable connections systems could be used if the design is focused on the actual system rather than existing solutions to different connections such as hinge systems.
3. Due to the limitations of space, multiple functions could be designed in a way that they could be removed. Therefore a removable system for all panels, when seen possible.
4. The possibility to integrate more than one single transformable connection into a furniture component.
5. Possible use of transformable connections also as surfaces for the furniture
6. Possibility to design neutral furniture components to allow the user to interpret how they may use the specific component rather than design specific and generic looking furniture components.

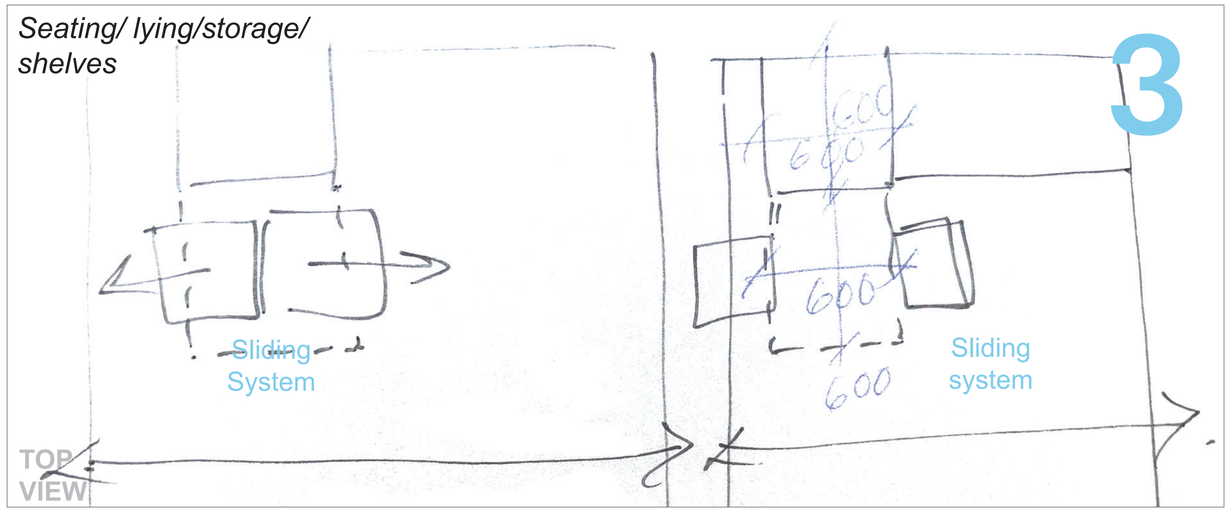
The conceptual design acted as a background reference / framework for the transformable connections to be further detailed and developed. It is important to be aware that these sketches only acted as a guideline and the design did evolve due to reasoning and manufacturing constraints throughout the design methodology process.



Images: Overlapping functions to find surfaces used for multiple functions (own illustration)







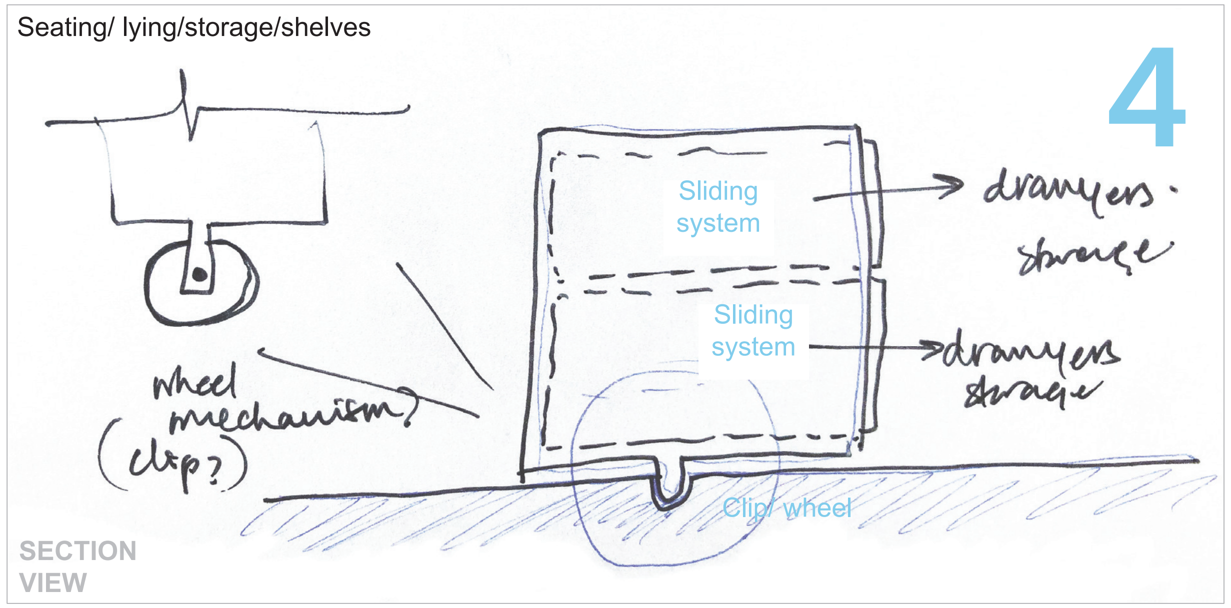


Illustration: Conceptual designs based off functional specifications drawn out from Human Dimensions and interior Spaces (1979) and other functional and conceptual design criteria. These initial conceptual designs will be further developed upon relatively important criteria according to each individual transformbale connection, prototyped, tested and validated. (own illustration)

WEIGHTING CRITERIA FOR ADDITIVE MANUFACTURING (SPECIFIC TO THIS DESIGN TASK)

The following are criteria for designing for additive manufacturing. They have been graded according to relative importance specific to this design task. The following graded criteria was based on:

- Machinability
- Eliminating the need for support material (most additive manufacturing machines do not have a dual nozzle. For the machines that do, more complex shapes with support material can be specifically designed according to machine options.
- Optimal printing
- Minimal material wastage
- Possible addition of structural strength based on print direction
- To enhance aesthetic qualities of the design

Prioritized in this design task:

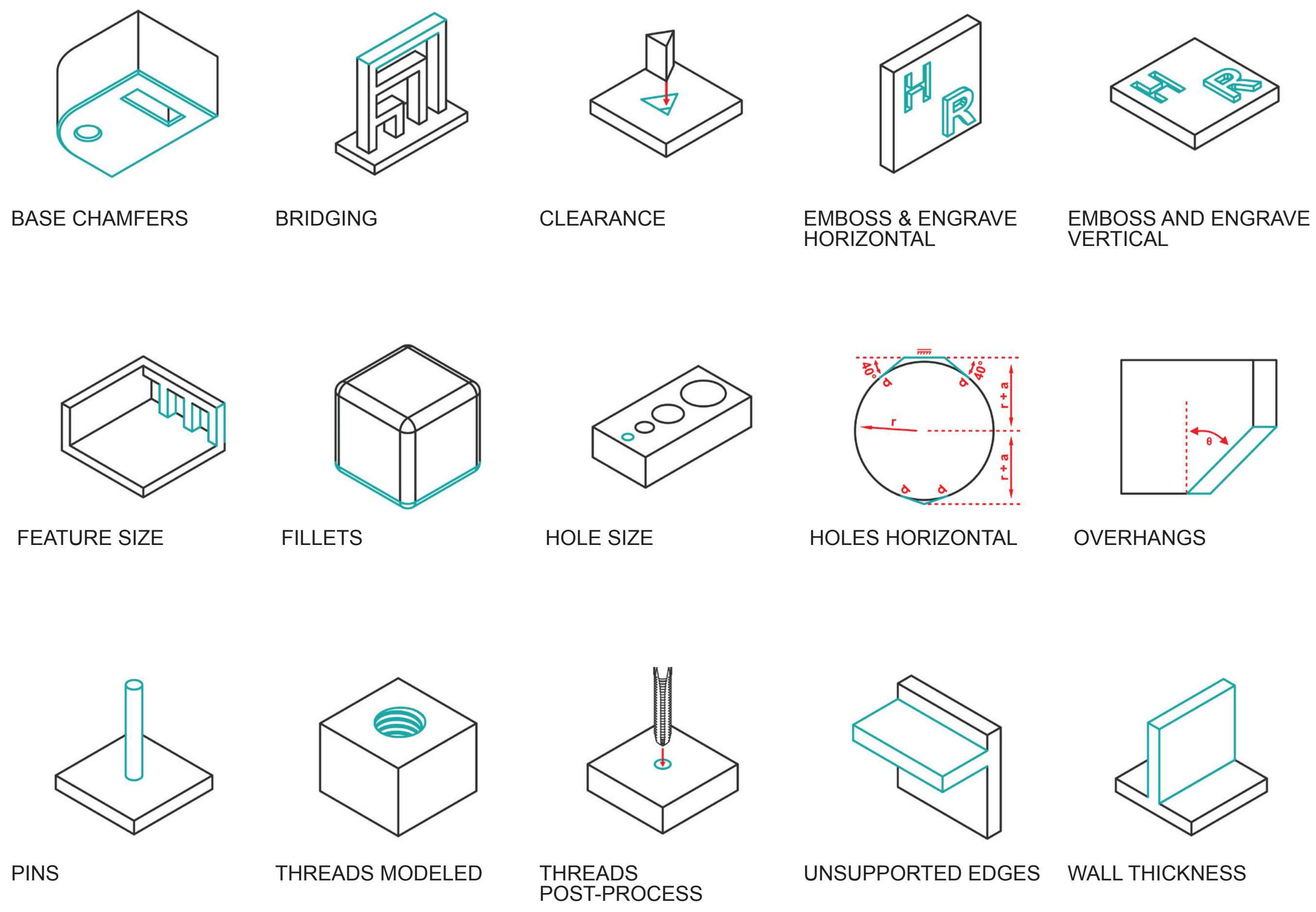
1. **Base chamfers** - faster print, neater print given the machine does not make any minute stops for turning its geometry
2. **Fillet** - Filleting of edges can provide a smoother finish when necessary, it may also add to the functionality of the design as a safety factor given that curved edges cause less collision damage.
3. **Clearance** - to be considered if two components are to be interconnected. Depending on the type of connection, the clearance may need to be tighter or looser.
4. **Emboss and engrave horizontally and vertically** - Possibility to use engraving as a method to create groves on the surface for different purposes such as to create friction, to create a specific surface feel or even for aesthetic design.
5. **Feature size** - attempt to create minimal features unless it adds functional purposes to optimize print, material, time and efficiency of the design.
6. **Hole size** - to be considered if using a clip system or adding functional details to the design. Minimum size of 2mm to be considered. Printing horizontal holes need to have a buffer of radius+0.3mm when printing, due to the layering system.

Not prioritized in this specific design task:

1. **Bridging and unsupported edges** - to avoid because of the need of support material if the bridging is over 10mm
2. **Overhangs** - To be considered if less than 50' and in most cases 30'. However, the strengths and weaknesses of having overhangs need to be considered specific to each design. In the case of this design task overhangs were not used because this may add limitations to the design and print possibilities.
3. **Threads molded** - Due to the differences in machines and variations of outputs due to these differences, screw type components were not designed.

The weighting of above criteria is specific to this design task. Some criteria were not considered for this design task due to the reasoning as explained next to its title. However, the suggested system of customizing transformable furniture is open to change according to different designer needs and functional applications. Therefore although the above criteria has been graded accordingly, this may change depending on the differences in projects. It is important to identify the most suitable criteria and prioritize according to the design vision. Rather than seeing the additive manufacturing criteria as a limitation, it could be seen as an added value to design and functionality when used in a correct manner. The luxury of being able to adapt the additive manufacturing criteria according to the need of the design and vice versa is a positive output of using additive manufacturing as the main manufacturing technique.

GENERAL CRITERIA TO BE CONSIDERED WHEN DESIGNING FOR ADDITIVE MANUFACTURING



Information and illustrations: HydraResearch3d.com/design-rules

Detailed descriptions of the above additive manufacturing criteria seen in Appendix III

RESEARCH BY DESIGN: DETAIL DESIGN

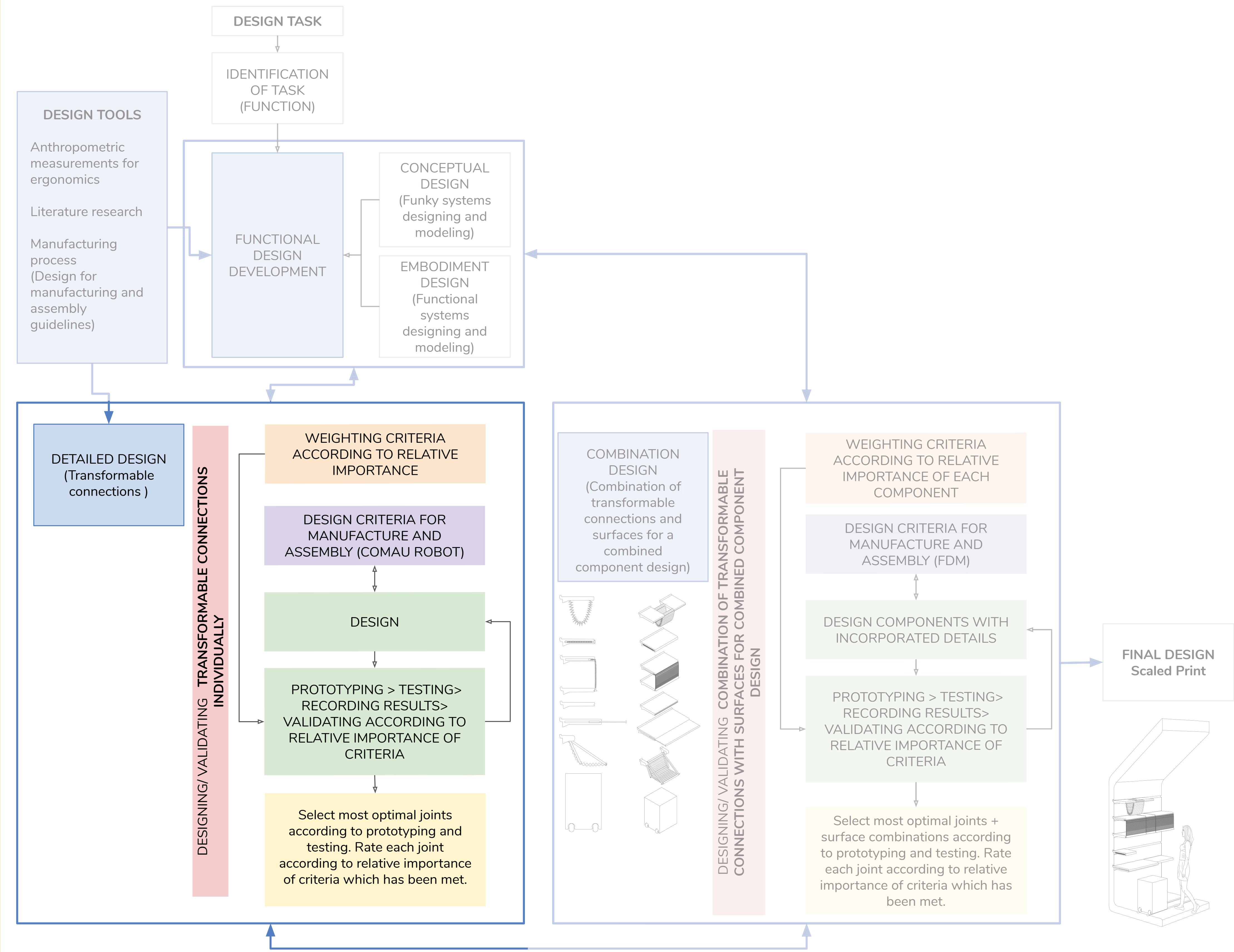


Image: Adapted methodology (own illustration)

DETAILED DESIGN

Detailed design is the firsts step towards designing the transformable connections.

According to functional design inputs and conceptual design development, four different types of transformable connection systems were chosen to be further developed, printed and tested according to a carefully determined set of validation criteria. These four types are as follows;

1. Sliding system
2. Folding system
3. Clip system
4. Main hanging system

According to the modular design with a focus on transformable connections, a common hanging system for all components will be designed. Having designed a standardized system and framework for all the transformable connections and components to extend from will further exaggerate the notion of modularity and mass customization. Once the main hanging system is designed, the transformable connections and the components will merely be an extension of the main hanging system. The following diagram further simplifies this connection.

8.1 DESIGN INPUTS FOR DETAILED DESIGN

Design inputs for detailed design are as follows;

1. Ergonomic data; Ergonomic measurements layered on top of each other to identify overlapping functions
2. Functional needs that arise from the overlapping of functions
3. Aesthetic design inputs from conceptual development.

   - FDM constraints for faster and more efficient printing.
   - Curved edges print more smooth and faster than square edges as the machine does not need to register a stop and turn on each bend.
   - Awareness of possible maximum overhang without having need to generate support material
   - Minimum and maximum layer thickness as a result of the FDM process and machine constraints
   - Minimum and maximum layer width as a result of the FDM process and machine constraints

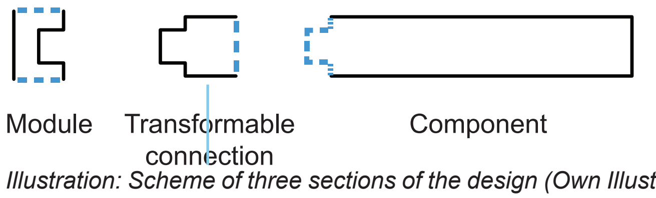


Illustration: Scheme of three sections of the design (Own Illustration)

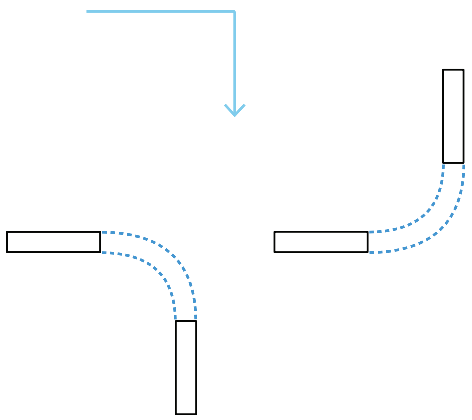


Illustration: Scheme for folding system (own illustration)

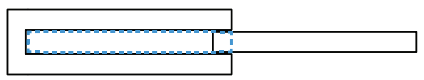


Illustration: Scheme for Sliding system (own illustration)

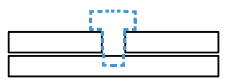


Illustration: Scheme for clip system (own illustration)

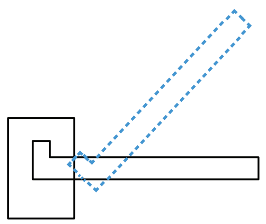


Illustration: Scheme for main hanging system (own illustration)

Design criteria for additive manufacturing needed to be given high consideration when being designed as all components and details are to be manufactured using additive manufacturing. The following are considerations for a successful design made for additive manufacturing.

In order to identify possible transformable connections, basic research into existing models were conducted. The following websites; thingverse.com, grabcad.com and free3d.com were searched based on key words such as 'hinges', 'connections' and 'joint'. Although these websites provided existing hinge designs and inspiration for possible transformable connections based on toys and origami designs, all the results were existing connections that were originally designed to be made using other materials such as steel. Neither of the results were purely designed to be adapted as transformable connections with the flexibility to be adapted into a modular system.

PROTOTYPING FOR BASIC FUNCTIONAL VALIDATION

According to the previously decided upon four types of transformable connection systems, The following prototypes were designed according to the design inputs for detailed design as listed above. Once designed according to the inputs they were printed using a Delta printer.

The material tested did prove positive for the folWlowing properties when tested and validated through Appendix I;

- Very good tensile strength
- Very good impact strength
- Excellent processability
- Clarity
- Reasonable thermal stability
- Is sensitive to UV


Photographs: Single layer printed PET using AM (own photographs)

8.2
TRANSFORMABLE CONNECTION 4: MAIN HANGING SYSTEM

WEIGHTING CRITERIA ACCORDING TO RELATIVE IMPORTANCE → **ADDITIVE MANUFACTURING CONSTRAINTS** → **DESIGN AND SELECT** → **PROTOTYPE** → **TEST > VALIDATE ACCORDING TO CRITERIA**

RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA

FOR TRANSFORMABLE CONNECTIONS

Primary criteria considered / To be considered against	Possibility to move in one direction when transforming	Load bearing of transformable connections	Maximum movement until faliure	max number of movement per lifespan	Bending radius	Expandability	Transformation distance	Single person handling	TOTAL SCORE
Possibility to move in direction when transforming		0	1	1	2	2	2	0	8
Load bearing of transformable connections	2		2	2	2	2	2	1	13
Maximum movement until faliure	1	0		1	2	2	2	0	8
max number of movements per lifespan	1	0	1		2	2	2	1	9
Bending radius	0	0	0	0		0	0	0	0
Expandability	0	0	0	0	0		0	0	0
Transformation distance	0	0	0	0	0	0		0	0
Single person handling	2	1	2	2	2	2	2		13

0- less important
1- equally important
2- More important

Anything below 5 not taken into consideration as the other criteria outweigh necessity

Design criteria in asscending relative importance for Sliding system

1 Possibility to move in direction when transforming
1 Bending radius
1 Expandability
2 Single person handling
3 Transformation distance
4 Maximum movement until faliure
4 max number of movements per lifespan

Table: weighting of criteria for the bending system and listed ascending; criteria of relative importance (own illustration)

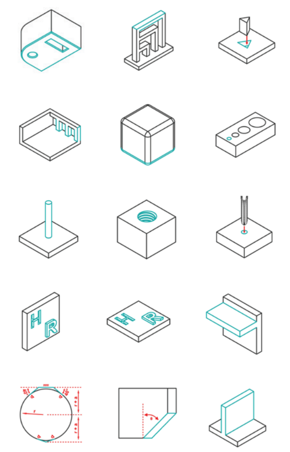


Illustration: Additive manufacturing constraints (illustrations: Hydra Research)

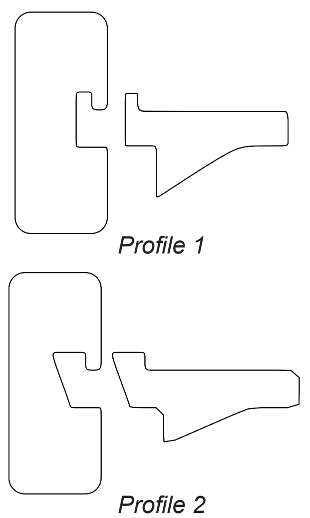


Illustration: Designed hinges according to relative importance of criteria and Additive manufacturing constraints (own illustration)

Illustration: Photographs of prototypes printed on a Delta printer using recycled PET as filament (own illustration)

	Hanging system			Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	**Success after prototyping**	**Success after testing**	**Total**
	Profile 1	PROTOTYPE	TEST	-	0	2	-	2	-	2	2	0	8
4	Profile 2			-	2	2	-	2	-	2	2	2	10

Table: Validating prototyped transformable connections according to criteria (own illustration)

GRADING SYSTEM

		Hanging
	Single	-
	Double	-
	Multiple	-
Direction	None	-
	Yes	2
Load bearing Capacity	No	0
	>90' - no	0
	<90 - yes	0
Minimum bending degree	none	2
	Yes	-
Expandability	No	-
	Yes	2
Single person handling	No	0
	Yes	-
Duplicate as surface	No	-
	Easy	2
Ease of handling	Medium	0
	Yes	2
Sucess after prototyping	No	0
	Yes	2
Success after testing	No	0
	Partially	1

Table: grading system for criteria for validation (own illustration)

TRANSFORMABLE CONNECTION 4: MAIN HANGING SYSTEM

Need for a standardized hanging system: To connect the transformable connections to the wall of the tiny house module

A tiny house is a small dwelling which could be less than 37m2 . When designing a tiny house, there are limitations of space purely due to its scale. Therefore when designing transformable interior components, the transformability of the space needed to be given priority. The initials stages of the design started off with components already connected to the module of the tiny house. Although customization is possible, this meant that the interiors would be permanently embedded into the wall of a tiny house. To allow maximum customization and personalization, a system where components could be freely interchangeable within the wall module drove to the designing of a hanging system for the components. In the case one component does not need to be used for an extended period of time, a hanging system allows the component to be removed and possibly stored away until its desired use. The hanging system also allows each module to be fully customized whenever the user sees needed by the means of rearranging the components or adding new components whenever they desire.

This created a need for a system where these transformable furniture components can be taken off and put back in whenever the user sees need. The illustration to the top left show a sliding system where the transformable furniture component can be moved through (Sliding mechanism) the groves of the module. However, this brought out the question that if there was a connecting module, these components would be removed, rather could only be removed when the modules are taken apart. This system will allow for customization by the user, but only at the time of installation and not through its life span.

The second system (Illustration: Left middle) is a clip type hanging system where the transformable furniture component is inserted into the specific designed groves of the living module and is supported by a structure (Illustration: left bottom). This system allows the components to be removed and inserted when the user may see fit. Therefore allowing for maximum personnalisation of transformable furniture components of this tiny house module.

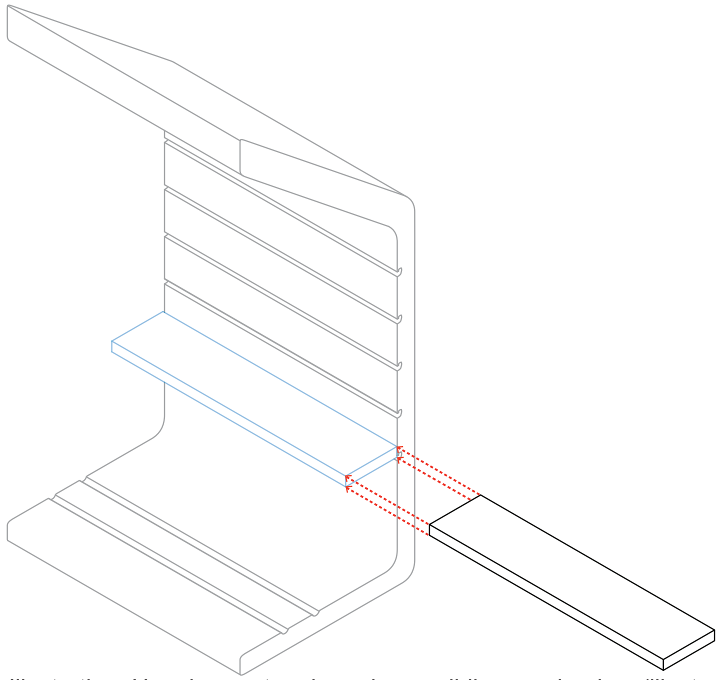


Illustration: Hanging system based on a sliding mechanism (illustrations: own illustration)

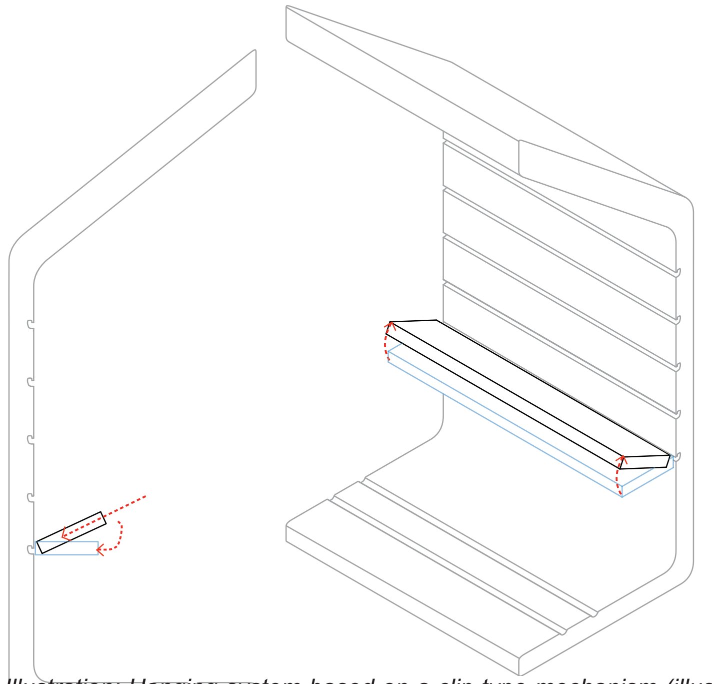


Illustration: Hanging system based on a clip type mechanism (illustrations: own illustration) further used for the development of this transforable connection (own illustration)

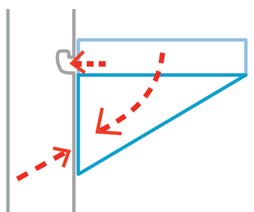


Illustration: Hanging system scheme (illustrations: own illustration)

Design criteria for the hanging system

The following system was based on the following requirements. The criteria below are specific to this design task (transformable interior component suing recycle PET for additive manufacturing) and proposed by needs and requirements based on previous research studies (under literature research as a section), functional design requirements, machinability and material used for the design;

1. Possibility to bear the load of any extensions designed beyond the transformable connection
2. Single person handling when transforming as a connection
3. Maximum possible movements during life span (In the case of the hanging system, this will be a minimum due to most components suspended from this hanging transformable system will be more permanent components. What will happen past the extension of this transformable connection will require to transform much more itself than the hanging system)
4. Possibility to allow movement in one direction if transformation requires such movement for 'installation purposes'.
5. Maximum possible movement or maximum possible holding of the movement in place until failure of the connection.

According to the above requirements, two systems were designed with continuous improvement made while prototyping. A click in place system was designed for ease of handling and to eliminate the need of installment before the living modules are out in place. This will allow continuous changes in customization even during the course of the living module being occupied. The components when not in use, could then be detached and stowed away as the user pleases.

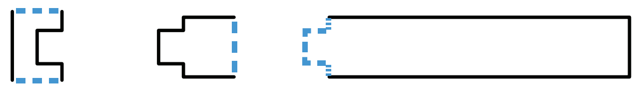


Illustration: Scheme of three sections of the design (Own Illustration)

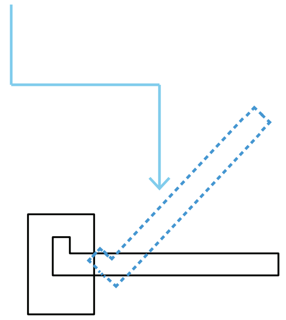
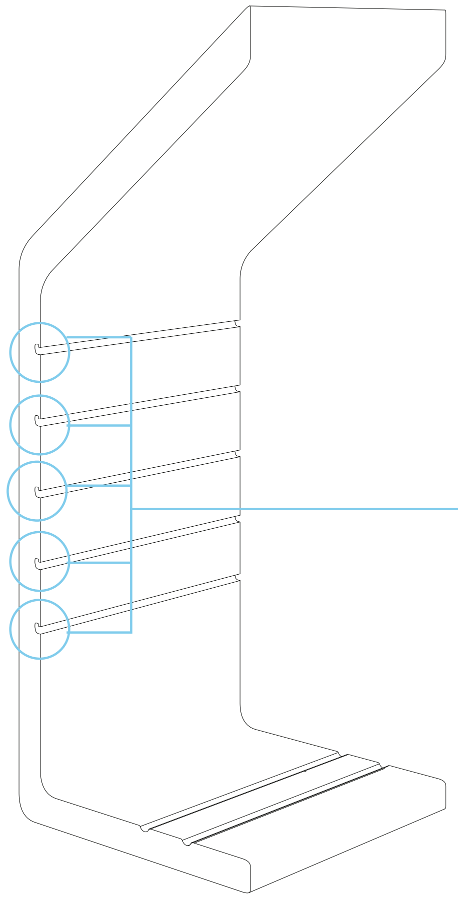
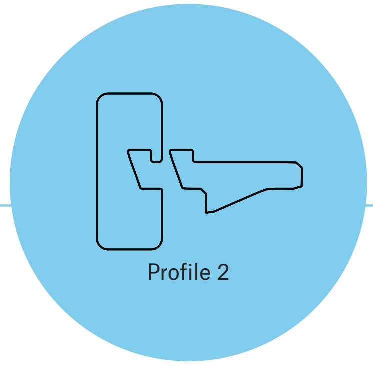


Illustration: Hanging system schematics (illustrations: own illustration)

ITERATIVE DESIGN, TESTING AND PROTOTYPING PROCESS FOR MAIN HANGING SYSTEM



Single multipurpose module with clip on grid system for customized functions (own illustrations)



Clip on hanging system

Iterations

Testing prototype

Testing prototype

Tested and validated design

Tested and validated design

The diagramming as seen on this page is of the iterative rapid prototyping of the hanging connection. The designs, although fit perfectly in a digital set up, needs to be prototyped and tested unless generative modeling is used in the validation process. Given that rapid prototyping is true to tits name, a quick prototype was printed, and tested in real time to see if the movement as needed for this connection to work did indeed function as designed. The iterations are small, yet effective in each round of prototyping. With the help of rapid prototyping, a final design, with its functionality validated by physical modeling was chosen as the final version of the hanging system. Each prototype was printed in under 10 minutes using a Delta printer and recycled PET filament.

8.3 TRANSFORMABLE CONNECTION 1: BENDING SYSTEM

Detailed descriptions of the design criteria can be seen on Appendix IIII

WEIGHTING CRITERIA ACCORDING TO RELATIVE IMPORTANCE → **ADDITIVE MANUFACTURING CONSTRAINTS** → **DESIGN AND SELECT** → **PROTOTYPE** → **TEST > VALIDATE ACCORDING TO CRITERIA**

RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA

FOR TRANSFORMABLE CONNECTIONS

Primary criteria considered / To be considered against

Primary criteria considered	Possibility to move in one direction w…	Load bearing of transformable connec…	Maximum movement until faliure	max number of movement per lifespa…	Bending radius	Expandability	Transformation dis…	Single perso…	TOTAL
Possibility to move in direction when transforming		2	2	1	1	1	2	1	10
Load bearing of transformable connections	0		0	1	0	0	0	1	2
Maximum movement until faliure	0	2		1	1	0	1	0	5
max number of movements per lifespan	0	2	1		0	0	1	1	5
Bending radius	1	2	1	1		2	2	1	10
Expandability	1	2	2	1	1		2	1	10
Transformation distance	1	2	1	1	0	0		1	6
Single person handling	1	2	1	1	1	1	1		8

0- less important
1- equally important
2- More important

Design criteria in asscending relative importance for Sliding system

1 Possibility to move in direction when transforming
1 Bending radius
1 Expandability
2 Single person handling
3 Transformation distance
4 Maximum movement until faliure
4 max number of movements per lifespan

Table: weighting of criteria for the bending system and listed ascending; criteria of relative importance (own illustration)

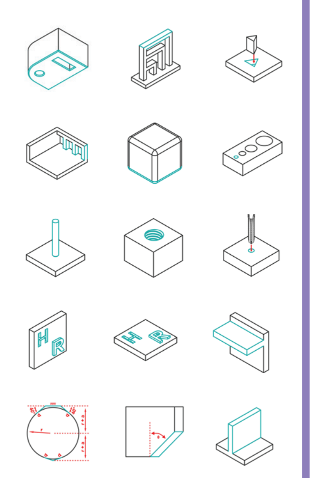


Illustration: Additive manufacturing constraints (illustrations: Hydra Research)

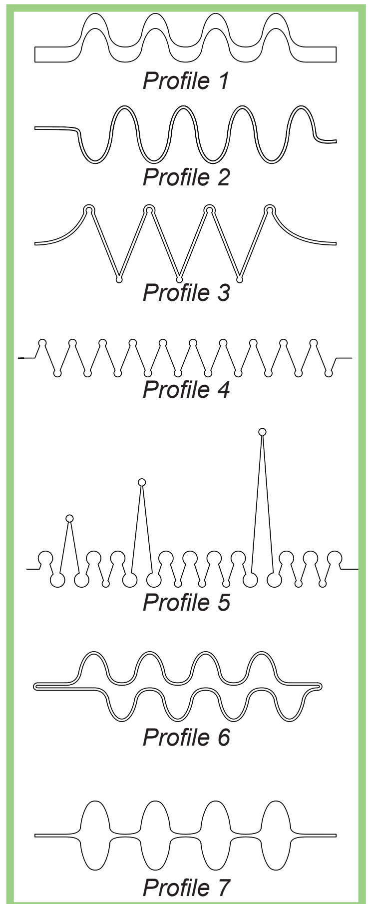


Illustration: Designed hinges according to relative importance of criteria and Additive manufacturing constraints (own illustration)

Illustration: Photographs of prototypes printed on a Delta printer using recycled PET as filament (own illustration)

PROTOTYPE TRANSFORMABLE CONNECTIONS / TEST ACCORDING TO CRITERA

Folding system	Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	**Success after prototyping**	**Success after testing**	**Total**
Profile 1	0	-	0	0	2	2	1	2	1	7
Profile 2	2	-	0	2	2	2	1	2	1	11
Profile 3	2	-	2	2	2	2	2	2	2	14
Profile 4	2	-	2	2	2	2	2	2	2	14
Profile 5	2	-	2	0	2	0	2	2	2	10
Profile 6	0	-	0	2	2	2	1	2	1	9
2 Profile 7	0	-	0	2	2	2	1	2	1	9

Table: Validating prototyped transformable connections according to criteria (own illustration)

GRADING SYSTEM

		Folding
	Single	2
	Double	2
	Multiple	1
Direction	None	0
	Yes	-
Load bearing Capacity	No	-
	>90' - no	0
	<90 - yes	2
Minimum bending degree	none	0
	Yes	2
Expandability	No	0
	Yes	2
Single person handling	No	0
	Yes	2
Duplicate as surface	No	0
	Easy	2
Ease of handling	Medium	1
	Yes	2
Sucess after prototyping	No	0
	Yes	2
Success after testing	No	0
	Partially	1

Table: grading system for criteria for validation (own illustration)

8.4 TRANSFORMABLE CONNECTION 2: SLIDING SYSTEM

Detailed descriptions of the design criteria can be seen on Appendix IIII

WEIGHTING CRITERIA ACCORDING TO RELATIVE IMPORTANCE → **ADDITIVE MANUFACTURING CONSTRAINTS** → **DESIGN AND SELECT** → **PROTOTYPE** → **TEST > VALIDATE ACCORDING TO CRITERIA**

RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA

FOR TRANSFORMABLE CONNECTIONS

Primary criteria considered / To be considered against	Possibility to move in single direction when transforming	Load bearing of transformable connections	Maximum movement until faliure	max number of movement per lifespan	Bending radius	Expandability	Transformation distance	Single person handling	TOTAL SCORE
Possibility to move in single direction when transforming		2	2	2	2	2	1	1	12
Load bearing of transformable connections	0		1	2	2	2	1	1	9
Maximum movement until faliure	0	1		2	2	2	1	0	8
max number of movements per lifespan	1	1	1		2	2	1	0	8
Bending radius	0	0	0	0		0	0	0	0
Expandability (for the hinge itself to expand as per design)	0	0	0	0	1		0	0	1
Transformation distance	0	0	0	0	0	2		0	2
Single person handling	1	1	2	2	2	2	2		12

0- less important
1- equally important
2- More important

Anything below 5 not taken into consideration as the other criteria outweigh necessity

Design criteria in asscending relative importance for Sliding system

1 Possibility to move in direction when transforming
1 Single person handling
2 Load bearing of transformable connections
3 Maximum movement until faliure
3 max number of movements per lifespan

Table: weighting of criteria for the bending system and listed ascending; criteria of relative importance (own illustration)

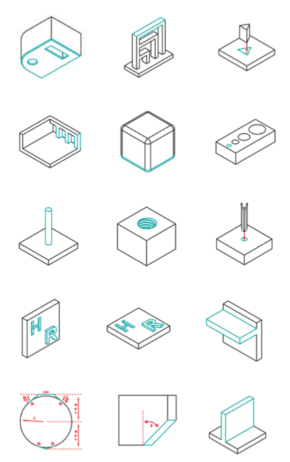


Illustration: Additive manufacturing constraints (illustrations: Hydra Research)

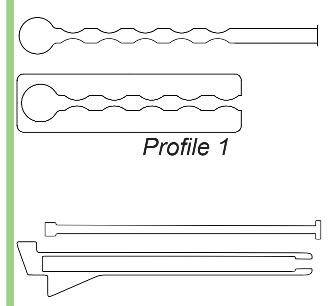


Illustration: Designed hinges according to relative importance of criteria and Additive manufacturing constraints (own illustration)

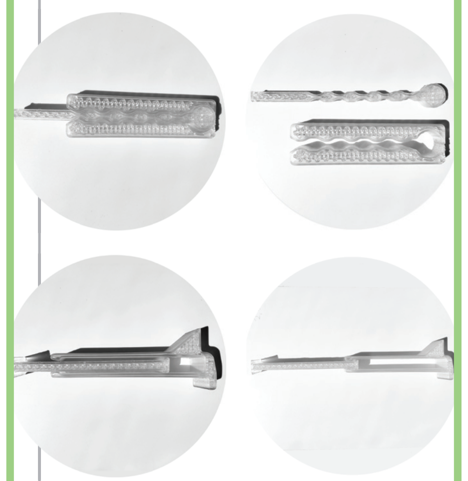


Illustration: Photographs of prototypes printed on a Delta printer using recycled PET as filament (own illustration)

	Sliding system	PROTOTYPE	TEST	Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	**Success after prototyping**	**Success after testing**	**Total**
	Profile 1			2	0	2	2	2	0	-	2	2	12
1	Profile 2			2	2	2	2	2	2	-	2	2	16

Table: Validating prototyped transformable connections according to criteria (own illustration)

GRADING SYSTEM

		Sliding
	Single	0
	Double	0
	Multiple	0
Direction	None	2
	Yes	2
Load bearing Capacity	No	1
	>90' - no	0
	<90 - yes	0
Minimum bending degree	none	2
	Yes	0
Expandability	No	2
	Yes	2
Single person handling	No	0
	Yes	2
Duplicate as surface	No	0
	Easy	-
Ease of handling	Medium	-
	Yes	2
Sucess after prototyping	No	0
	Yes	2
Success after testing	No	0
	Partially	1

Table: grading system for criteria for validation (own illustration)

8.5 TRANSFORMABLE CONNECTION 3: CLIP SYSTEM

Detailed descriptions of the design criteria can be seen on Appendix IIII

WEIGHTING CRITERIA ACCORDING TO RELATIVE IMPORTANCE | **ADDITIVE MANUFACTURING CONSTRAINTS** | **DESIGN AND SELECT** | **PROTOTYPE** | **TEST > VALIDATE ACCORDING TO CRITERIA**

RELATIVE IMPORTANCE OF DETAILED DESIGN CRITERIA

FOR TRANSFORMABLE CONNECTIONS

Primary criteria considered / To be considered against	Possibility to move in one direction when transforming	Load bearing of transformable connections	Maximum movement until faliure	max number of movement per lifespan	Bending radius	Expandability	Transformation distance	Single person handling	TOTAL SCORE
Possibility to move in direction when transforming		0	0	0	0	0	0	0	0
Load bearing of transformable connections	0		1	1	1	2	0	1	6
Maximum movement until faliure	2	1		1	2	2	2	1	11
max number of movements per lifespan	2	1	2		2	2	2	1	12
Bending radius	2	1	1	1		2	2	1	10
Expandability	0	0	0	0	0		0	0	0
Transformation distance	0	0	0	0	0	0		0	0
Single person handling	2	2	1	1	2	2	2		12

0- less important
1- equally important
2- More important

Anything below 5 not taken into consideration as the other criteria outweigh necessity

Design criteria in asscending relative importance for Sliding system

1 Single person handling
1 max number of movements per lifespan
2 Maximum movement until faliure
3 Bending radius
4 Load bearing of transformable connections

Table: weighting of criteria for the bending system and listed ascending; criteria of relative importance (own illustration)

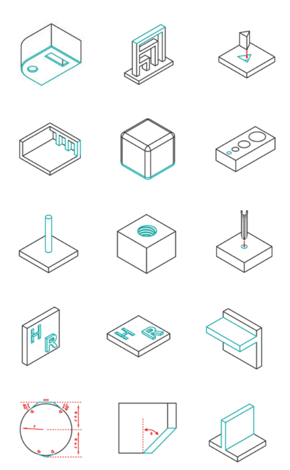


Illustration: Additive manufacturing constraints (illustrations: Hydra Research)

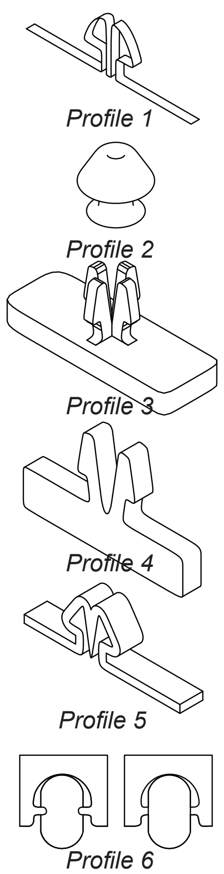


Illustration: Designed hinges according to relative importance of criteria and Additive manufacturing constraints (own illustration)

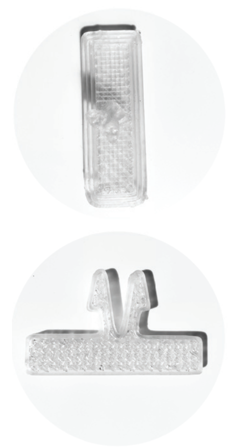


Illustration: Photographs of prototypes printed on a Delta printer using recycled PET as filament (own illustration)

	Clip system	PROTOTYPE	TEST	Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	Success after prototyping	Success after testing	Total
	Profile 1			-	0	0	-	2	-	-	2	0	4
	Profile 2			-	2	2	-	2	-	-	0	0	6
	Profile 3			-	2	2	-	2	-	-	0	0	6
	Profile 4			-	2	2	-	2	-	-	2	2	10
	Profile 5			-	2	2	-	2	-	-	2	0	8
3	Profile 6			-	2	2	-	2	-		2	2	10

Table: Validating prototyped transformable connections according to criteria (own illustration)

GRADING SYSTEM

		Clip
Direction	Single	-
	Double	-
	Multiple	-
	None	-
Load bearing Capacity	Yes	2
	No	0
Minimum bending degree	>90' - no	2
	<90 - yes	0
	none	2
Expandability	Yes	-
	No	-
Single person handling	Yes	2
	No	0
Duplicate as surface	Yes	-
	No	-
Ease of handling	Easy	-
	Medium	-
Sucess after prototyping	Yes	2
	No	0
Success after testing	Yes	2
	No	0
	Partially	1

Table: grading system for criteria for validation (own illustration)

8.6 PROTOTYPED TRANSFORMABLE CONNECTIONS

The following images are a series of transformable connections that were prototyped according to the digital drawings on the right. Some transformable connections such as the bending connections performed beyond expectation and also suggested a few extra ways of transforming these connections to achieve more uses than previously predicted when hey were diagrammed.
As examples; the bending connections, designed only to be purposed as a connection, could also be printed in a large scale the be used as a surface for sitting.

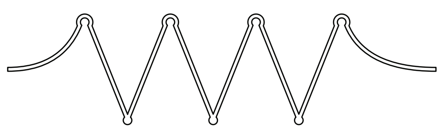


Image: folding system 1 (own illustration)

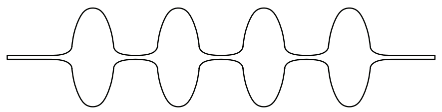


Image: folding system 2 (own illustration)

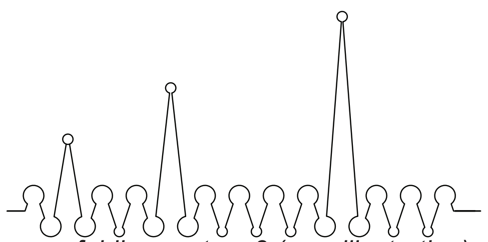


Image: folding system 3 (own illustration)

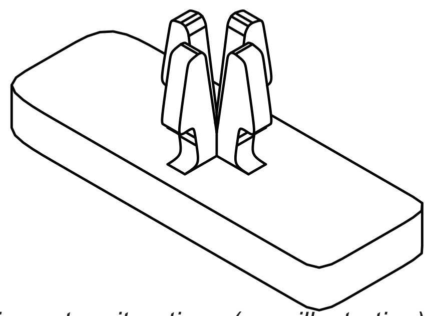


Image: clip system iterations (own illustration)

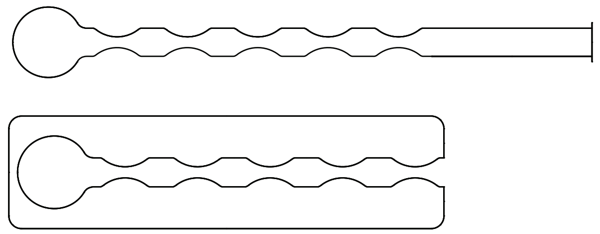
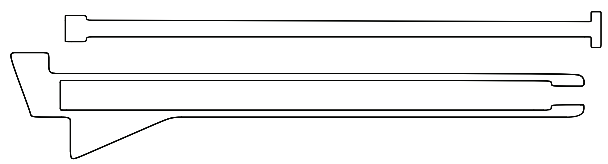


Image: Sliding system 1 (own illustration)



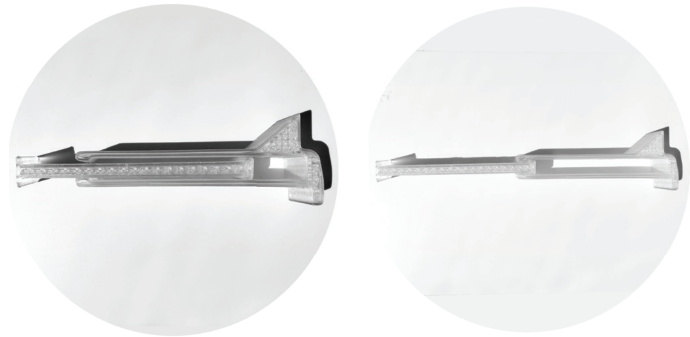


Image: Sliding system 2 (own illustration)

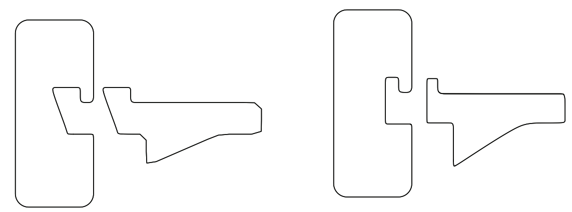


Image: Hanging system iterations (own illustration)

Although the above systems were printed, not every single prototype was a success. As example, the clip system as shown illustrated and photographed, was not a success due to the machinability (oozing of extra material causing the inability to separate the 4 extrusions which would become the slip). This can be seen through the images below.

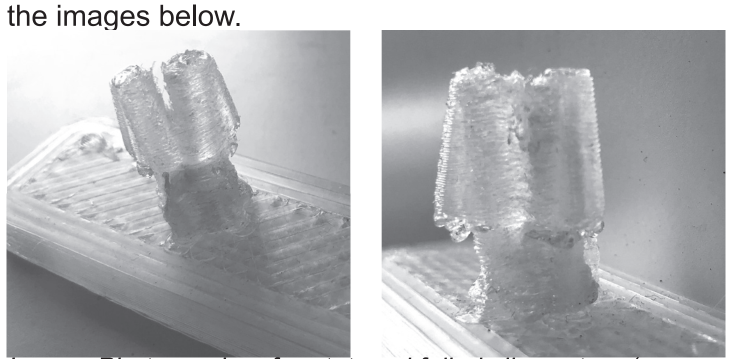


Image: Photographs of prototyped failed clip system (own illustration)

However, the limitations of machinability can differ comparative to machine size and object size. If the component was in a larger scale, there may not have been problems of oozing and layers sticking together.

However, many of the other prototypes were successful, specially the bending profiles. They were able to move and with hold its shape as expected, Further proving validity of PET as a material with high flexural strength (Appendix I).

8.7 RAPID PROTOTYPING

Prototyping was selected as one of the sub research questions for this design task. Prototyping was given such significance due to the method of manufacturing having only two variants which are time and material, therefore customization, and rapid prototyping can be done in a fast manner (Pereira et.al 2019). The producing of quick, smaller scaled models for testing were due to clarifying the following;

1. Properties of recycled PET
2. Does the selected mechanism work as designed
3. Quick and necessary changes to be made in order for the transformable connections to work.
4. To identify the best print direction depending on the different transformable connections

Through the design process prototyping was mainly used to print quick iterations, and test them in accordance with the design criteria and the physical movement of either transforming as a connection or in the case of the hanging system, to physically hand on the wall system.
An example of the iterative process for the hanging system can be seen below.

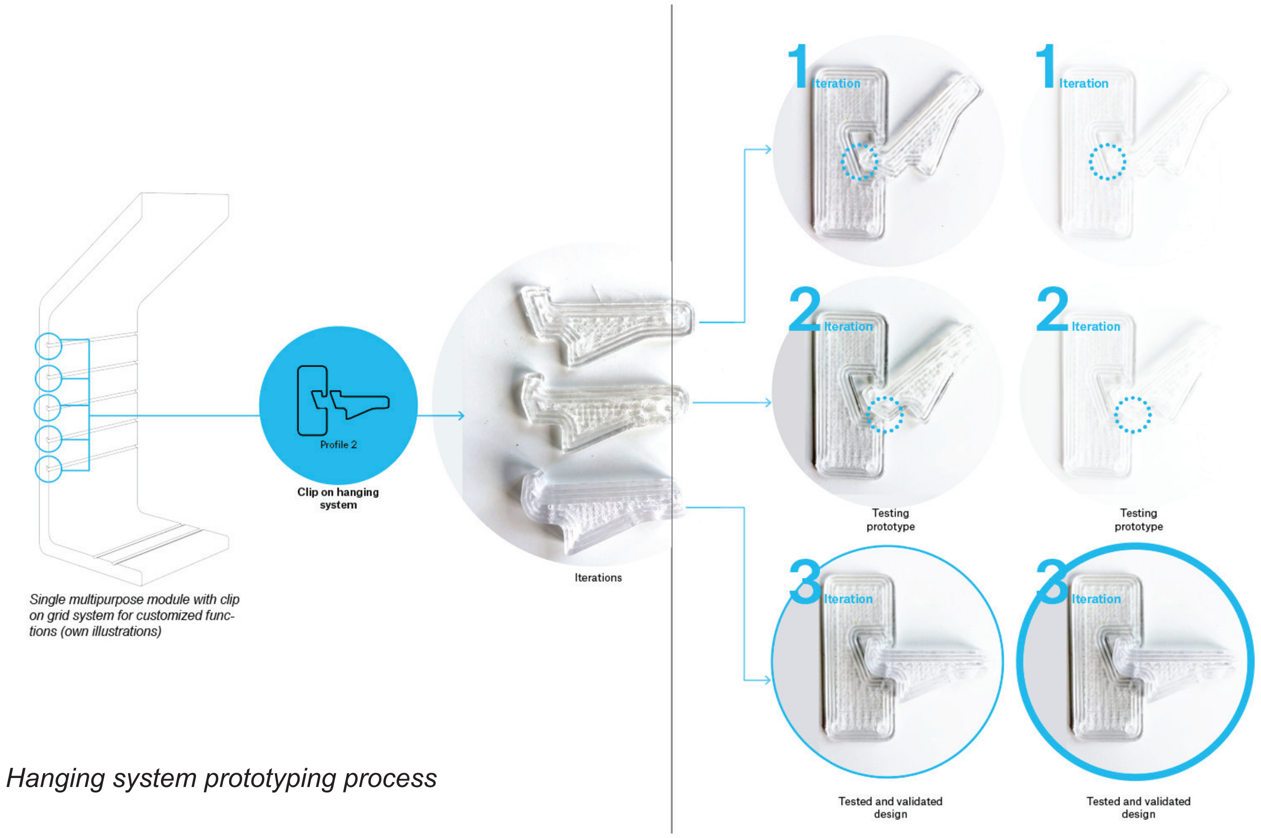


Image: Hanging system prototyping process

Significant results of having used rapid prototyping for this specific design task are;

1. It was evident that recycled PET when printed using additive manufacturing (Delta printer) at a material thickness of 1.4mm (scaled down to fit the delta printer) did have the desired strength to snap back into shape when required as evident in the profiles for the bending system.

Image: Testing recycled PET print for material performance

2. Repetitive prototyping for small iterations allowed for improvements to be made that possible could have been overlooked in the digital design phase. Once a design is printed and tested physically, small adjustments better suitable for handling have been made in each of the designs.

Image: Quick iterations to validate a single design

3. Certain designs, although works perfectly in a digital design, did not print as expected due to the machinability. Certain limitations such as material oozing(that connected separated surfaces together), material shrinkage (Curvature of the bottom layers compared to the top layers) due to the layer cooling process did affect the overall design and validation process.

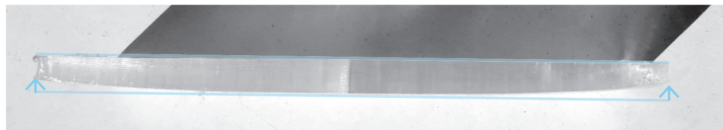


Image: layer contraction due to uneven heat distribution

4. Certain prints did not have a smooth output due to external factors, therefore it is important to keep in mind that the first print may not always be the final print.

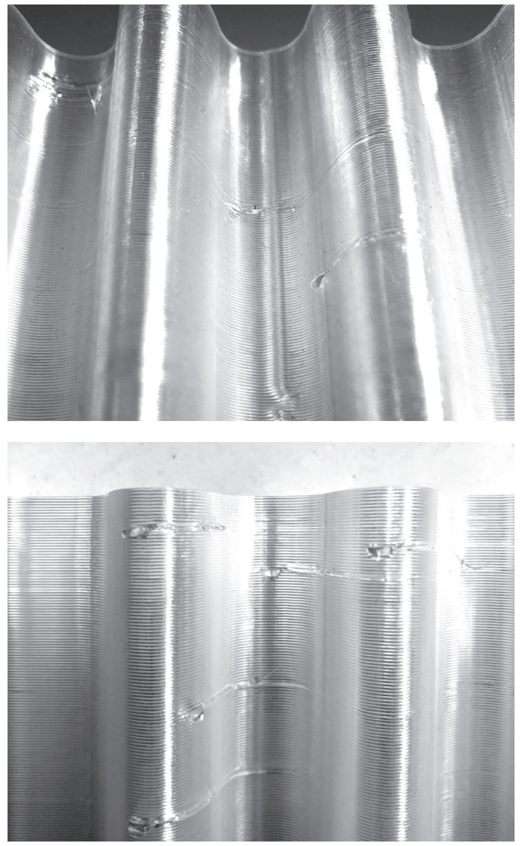
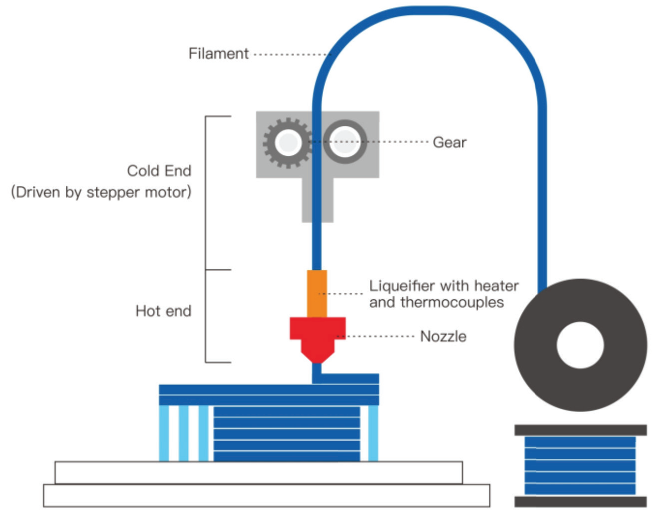


Image: Oozing of layers causing and uneven surface

5. Considering that the initial aim of this project pre-corona was to print a 1:1 scaled model, it is important to note that there may be similar problems when it comes to printing the same object using a Comau robot arm. Also given that the mode of material input for the Delta is through a spool, material input for the Comau robot arm is in the form of pellets that need to be fed through a hot melted extrusion process, there may be significant differences in the print output of the potential 1:1 scaled model. Therefore there is no specific method of determining the output of either print as they both can be affected by external influences during the printing process.



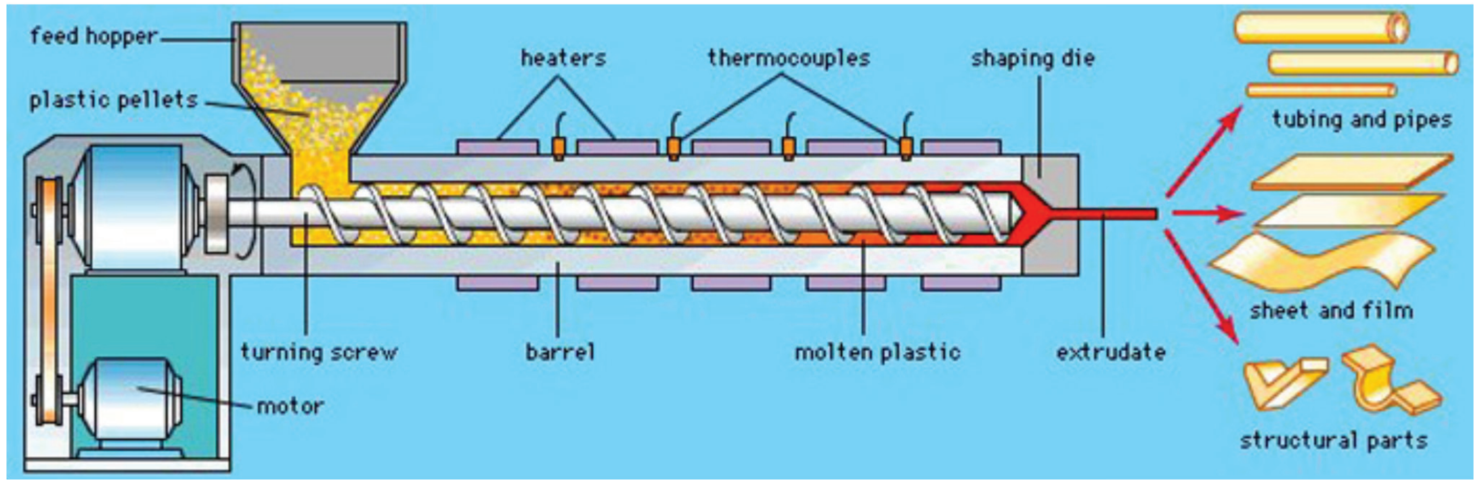


Image: Filament extruder mechanism similar to the one used for the Comau NJ60 2.2

Therefore when considering to what extent prototyping can be incorporated into the research by design process, the above factors need to be taken into account. Due to the variable nature of rapid prototyping, it may not be the most reliable process if multiple of the same object need to be printed in the exact same condition, there may always be slight variations in the layers (Based on the prototyping done for this . However, these small variations may or may not have an impact on the final design depending on the different needs specified for different design tasks.

Prototyping in the case of this design task was extremely helpful for printing quick iterations to test the material along with the specific shapes. Prototyping allowed for a stronger conversation to happen between simple designs and their physical performance. The ability for design to be influenced by the prototyping process shows a visible dialog between the designer and the manufacturing process; both needing to work hand in hand based on each process's feedback for a successful design.

Prototypes need to be adapted and designed according to additive manufacturing criteria. This is mainly due to the machinability and possibility of optimizing the print in terms of print time, material usage and structural strength. Additive manufacturing criteria has been identified and weighted according to relative importance

POSITIVE OUTCOMES (STRENGTHS)	NEGATIVE OUTCOMES (WEAKNESSES)
1. Additive manufacturing allows for mass customization where quick iterations can be made and manufactured without having to depend on traditional and expensive manufacturing.	1. Limitation of size of the print beds based on the 3D printer
2. Given that the only variables for additive manufacturing are time, material and energy consumed, the cost of production for 1 piece or 1000 pieces remains the same.	2. Limitations of available material
3. The possibility to print curved edges allowing for a smoother and faster print. This may also be approached as an aesthetic design decision.	3. Available material may not always suit the necessary design task
4. Possible manipulation of print direction to increase or decrease structural properties of the material without having to incorporate a second material	4. If overhangs need to be printed, a second material as a support needs to be used in a dual nozzle system.
5. Additive manufacturing allows for the designer to have full control over print options and settings	5. Variations that may occur due to external influences such as temperature and solar exposure when printing
6. Complicated forms can be printed without the need of sophisticated/ traditional manufacturing methods.	6. Manufacturing may take time if large quantities need to be printed comparative to methods such as extrusion molding where larger quantities are more economical.
7. Ability to print fast prototypes to understand form.	7. Additive manufacturing machine has its own set of limitations that may not suit all design tasks.

Table: Strengths and weaknesses of using additive caricaturing as a manufacturing technique

specific to this design task in page 74 of this report. Designing according to machinability did have both positive and negative effects. The following table summarizes the positives and negatives of designing for manufacturing using additive manufacturing.

8.8 VALIDATION- DETAIL DESIGN

In order to validate the design of the transformable connections, they need to be able to function according to a few different criteria. The criteria decided for validating the transformable connections are as follows;

1.
2. Possibility to move in one direction
3. Load bearing capacity
4. Bending capacity, degree
5. Possibility to expand
6. Single person handling
7. Possibility to duplicate as a surface
8. Ease of handling
9. Success after prototyping
10. Success after testing

Each criteria may affect different types of systems in slightly different ways. In order to quantify these changes, a grading system for the importance of each criteria against the different systems can be seen to the right of the verification chart. The need for a grading system was due to the inability of naming the success of each criteria if or not met in a cohesive manner. By grading on a scale of 0 and 2, the result of validating each criteria according to the performance of the transformable connection will have a similar grading system to that of weighting the criteria pre-designing of each transformable connection.

Profiles with the highest grading after being validated against the criteria, were decided as the most optimal design of transformable connections for that specific transformable connection system. Although the most optimal design is being chosen, this should not outweigh the possibility of incorporating other transformable connection designs into a combined design of connection and surfaces when seen fit. If a connection fails to successfully function according to set criteria after being printed, such transformable connections will be removed from being considered for and further integration into designs.

PROTOTYPE JOINTS
TEST JOINTS ACCORDING TO RELATIVE IMPORTANCE OF DESIGN CRITERIA

	Type/name	Possibility to move in a direction	Load bearing capacity	Bending capacity (degree)	Possibility to expand	Single person handling	Possibility of duplicating as a surface	Ease of handling	**Success after prototyping**	**Success after testing**	**Total**
	Sliding system										
	Profile 1	2	0	2	2	2	0	-	2	2	12
1	Profile 2	2	2	2	2	2	2	-	2	2	16
	Folding system										
	Profile 1	0	-	0	0	2	2	1	2	1	7
	Profile 2	2	-	0	2	2	2	1	2	1	11
	Profile 3	2	-	2	2	2	2	2	2	2	14
	Profile 4	2	-	2	2	2	2	2	2	2	14
	Profile 5	2	-	2	0	2	0	2	2	2	10
	Profile 6	0	-	0	2	2	2	1	2	1	9
2	Profile 7	0	-	0	2	2	2	1	2	1	9
	Clip system										
	Profile 1	-	0	0	-	2	-	-	2	0	4
	Profile 2	-	2	2	-	2	-	-	0	0	6
	Profile 3	-	2	2	-	2	-	-	0	0	6
	Profile 4	-	2	2	-	2	-	-	2	2	10
	Profile 5	-	2	2	-	2	-	-	2	0	8
3	Profile 6	-	2	2	-	2	-		2	2	10
	Hanging system										
	Profile 1	-	0	2	-	2	-	2	2	0	8
4	Profile 2	-	2	2	-	2	-	2	2	2	10

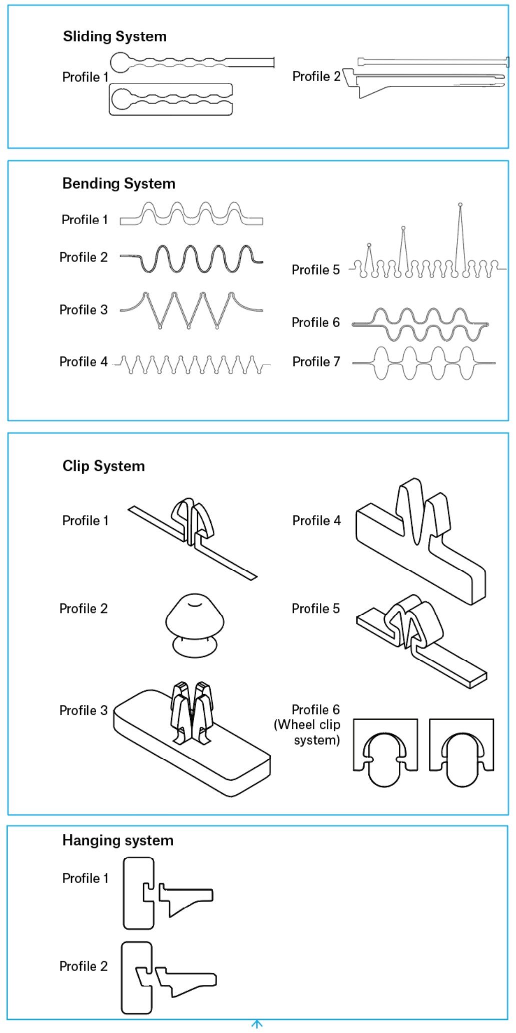


Table: Validation of detail designs of transformable connections according to criteria (own illustration)

GRADING SYSTEM

		Sliding	**Folding**	**Clip**	**Hanging**
	Single	0	2	-	-
	Double	0	2	-	-
	Multiple	0	1	-	-
Direction	None	2	0	-	-
	Yes	2	-	2	2
Load bearing Capacity	No	1	-	0	0
	>90' - no	0	0	2	0
	<90 - yes	0	2	0	0
Minimum bending degree	none	2	0	2	2
	Yes	0	2	-	-
Expandability	No	2	0	-	-
	Yes	2	2	2	2
Single person handling	No	0	0	0	0
	Yes	2	2	-	-
Duplicate as surface	No	0	0	-	-
	Easy	-	2	-	2
Ease of handling	Medium	-	1	-	0
	Yes	2	2	2	2
Sucess after prototyping	No	0	0	0	0
	Yes	2	2	2	2
Success after testing	No	0	0	0	0
	Partially	1	1	1	1

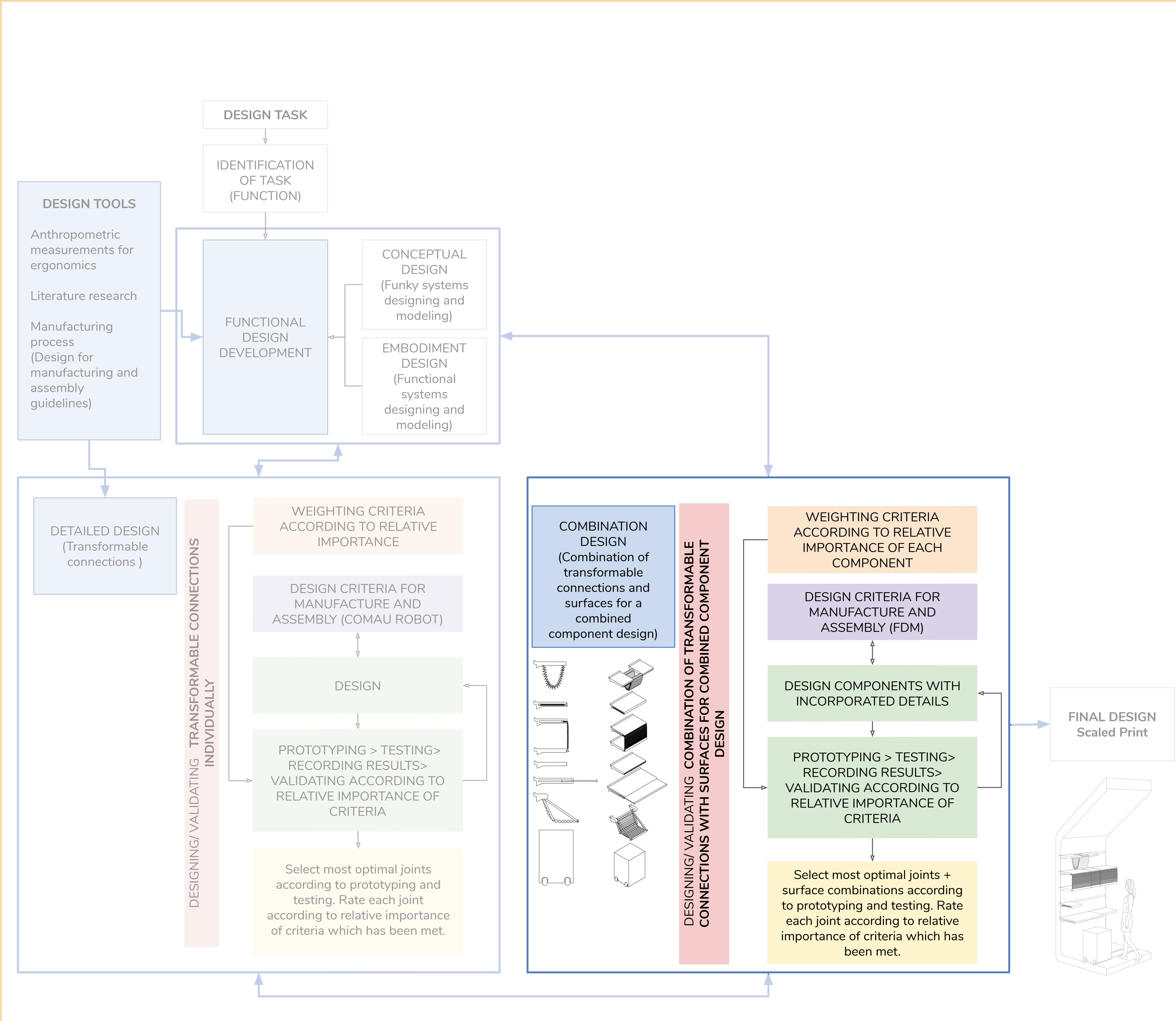
SUMMARY

Functional design development: This phase was constructed purely for the understanding and recording of measurements based on ergonomic data. The use of ergonomic measurement and other information such as maximum and minimum needed space needed for certain functions allowed for a baseline to start designing from.

Conceptual design/ embodiment design: A few design constraints based on functional design constraints and conceptual design constraints allowed for the development of the conceptual design for this design task. Sketching, diagramming, and rough prototyping was used as initial help for designing while ergonomic measurements added a strong guide to the entire conceptual design phase.

Detailed design: The detailed design phase was purely based on its own part of the methodology. Starting from weighing of the criteria based on relative importance, implementing additive manufacturing criteria as one main input for designing further, designing, prototyping, testing and ending with validating according to criteria set out by weighting them. It is important to note that all the above steps were most definitely influenced by each other and it was a more cohesive contribution to finishing the design rather than it being a step by step process. Once each detail was fed through this process, a few were cosen to be further developed in the combination design phase.

9. RESEARCH BY DESIGN: COMBINATION DESIGN



COMBINATION DESIGN

The combination design phase is to combine transformable connections with surfaces to design functional components. **This phase is only an example of a single interpretation of what the transformable connections combined with surfaces could be. This process, as an example, is a combinations of the transformable connections proposed in the previous design phase adopted and incorporated into transformable furniture components.**

The following explanations will describe the process used to design one of the components and at the end, more examples of combinations will be shown as further examples.

APPROACH

WEIGHTING CRITERIA

In order to design a single component, certain criteria need to be considered for a successful design. The weighting chart below is an example for one of the components designed.

The component used as an example for the combination design phase is component 2: A flat surface with a sliding system built within.

The weighting of criteria for each different component with a different function will be unique. To design the above system criteria unique to this particular component will be weighted as shown in the graph below. The criteria used for weighting are as such;

1. Load bearing >50kg (weight of one person)
2. Load bearing <50kg (weight of regular goods)
3. Can be duplicated as a surface
4. Possibility to adapt to more than one function
5. Can be detached from wall
6. Ease of handling
7. Single person handling
8. Design for optimal print and material use.

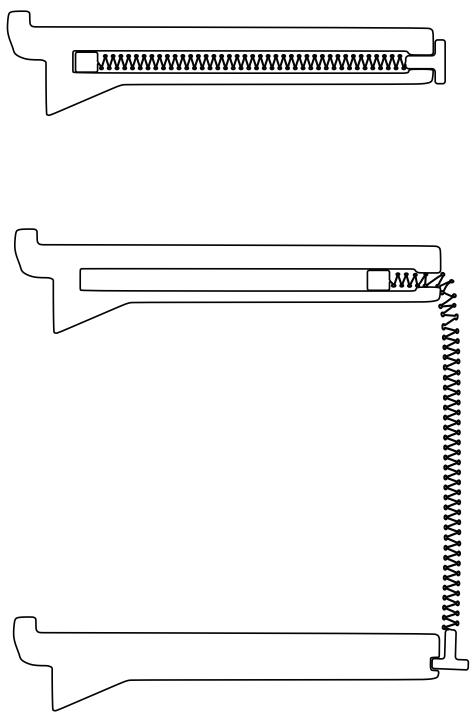


Illustration: Component 2: A flat surface with a built-in sliding system- section (own illustration)

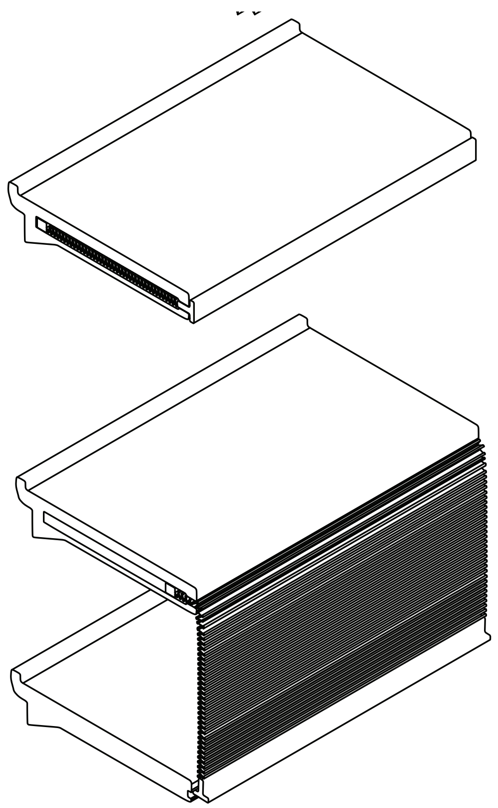


Illustration: Component 2: A flat surface with a built-in sliding system- isometric view (own illustration)

As a result of weighting the criteria, the following were decided as the main criteria to be considered for designing the component 2.

1. Single person handling
2. Design for optimal print and material use
3. Load bearing <50kg (weight of regular goods)
4. Ease of handling
5. Can be duplicated as a surface
6. Possibility to adapt to more than one function
7. Can be detached from wall

Accordingly the combination design for this component will occur

DESIGN CRITERIA FOR ADDITIVE MANUFACTURING

Criteria for additive manufacturing as illustrated and explained in page 67 will be considered when designing components for this particular manufacturing method.

Please refer to page 67 for more tail on the following criteria specific to additive manufacturing;

1. Base chamfering
2. Embossing and engraving
3. Overhangs
4. Unsupported holes
5. Wall thicknesses
6. Pins
7. Feature sizing
8. Base corners
9. Bridging
10. Filleting edges
11. Modelling threads
12. Clearances
13. Hole sizing
14. Unsupported edges

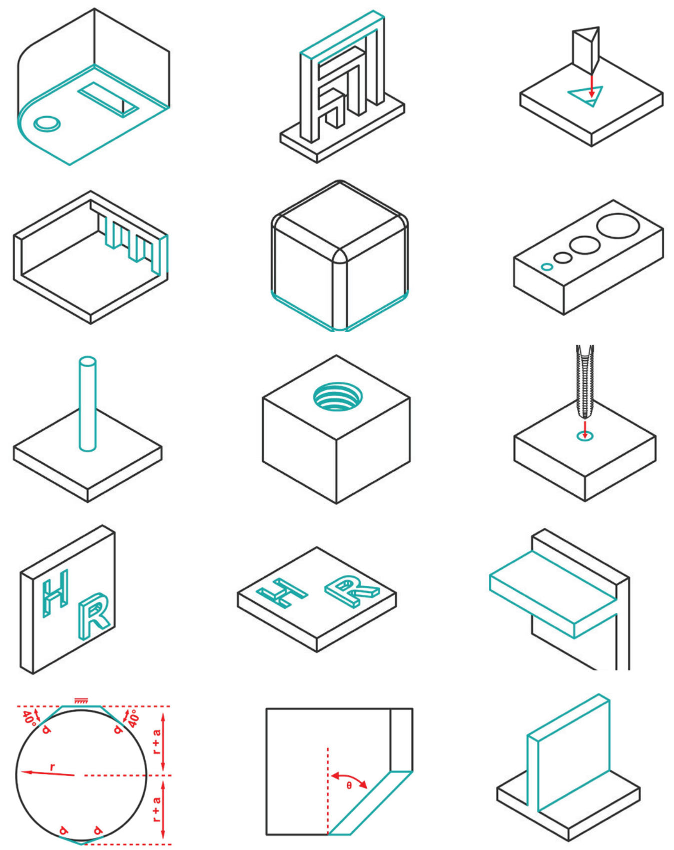


Illustration: Additive manufacturing constraints (illustrations: Hydra Research)

RELATIVE IMPORTANCE OF COMBINATION DESIGN CRITER

FOR TRANSFORMABLE CONNECTIONS

Primary criteria considered	Load bearing >50kg (weight of one person)	Load bearing <50kg (weight of regular goods)	Design for optimal print and material use.	Can be duplicated as a surface	Possibility to adapt to more than one function	Can be detached from wall	Ease of handling	Single person handling	
	To be considered against								
Load bearing >50kg (weight of one person)		0	0	0	0	0	0	0	0
Load bearing <50kg (weight of regular goods)	2		1	1	1	1	1	1	8
Design for optimal print and material use.	2	1		2	2	2	1	1	11
Can be duplicated as a surface	2	1	1		1	1	1	1	8
Possibility to adapt to more than one function	2	0	1	1		1	1	1	7
Can be detached from wall	2	0	0	1	1		1	1	6
Ease of handling	2	1	1	1	1	1		1	8
Single person handling	2	2	1	2	2	2	1		12

0- less important
1- equally important
2- More important

Anything below 5 not taken into consideration as the other criteria outweigh necessity

Design criteria in asscending relative importance for Sliding system

1 Single person handling
2 Design for optimal print and material use.
3 Load bearing <50kg (weight of regular goods)
3 Can be duplicated as a surface
3 Ease of handling
4 Possibility to adapt to more than one function
5 Can be detached from wall

Table: weighting of criteria for component 2 of combination design and listed ascending; criteria of relative importance (own illustration)

DESIGNING, PROTOTYPING, TESTING AND VALIDATING

Once the relative importance criteria and additive manufacturing criteria have been considered, accordingly, a combination design can be developed. Each component will have the hanging system as the main starting point and then it can extend outwards depending on the chosen function. One or more transformable connects may be combined to design one combination design depending on the functional need of the component itself.

REASONING FOR AN EXTRUDED TYPE PROFILE:

An extruded profile type was chosen for this design and some more of the other exemplary designs due to the following reasons;

1. Ease of printing: an extruded profile is a simple print process for smaller scale printers that can only build up upon layers.
2. Aesthetic properties of having single directional groves on the surface.
3. Strength
    - It is possible to adjust the amount of support material that can be printed on the inside of the profile therefore a component's structural strength can be adjusted according to the functional needs.
    - When printing, there is added structural strength depending on the direction of print and direction of load to be bared.

Once designed and prototyped, the component will be validated using the following format. Certain criteria needed to be met for the component to be successful as a functional design. Criteria used to validate the combination designs are as follows;

1. To the transformable connections complement the possible/ chosen function for the designed component
2. Is the component designed for one or more functions
3. Can the component bear weight? If so, to what extent?
4. Is it possible to adapt the function of the component at different times
5. Ease of handling
6. Single person handling
7. Success after prototyping
8. Success after testing

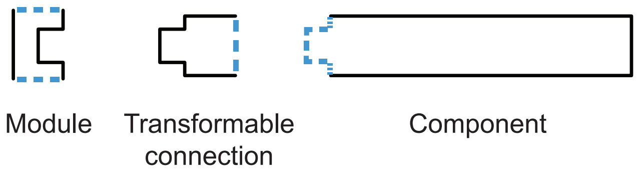


Illustration: Scheme of three sections of the design (Own Illustration)

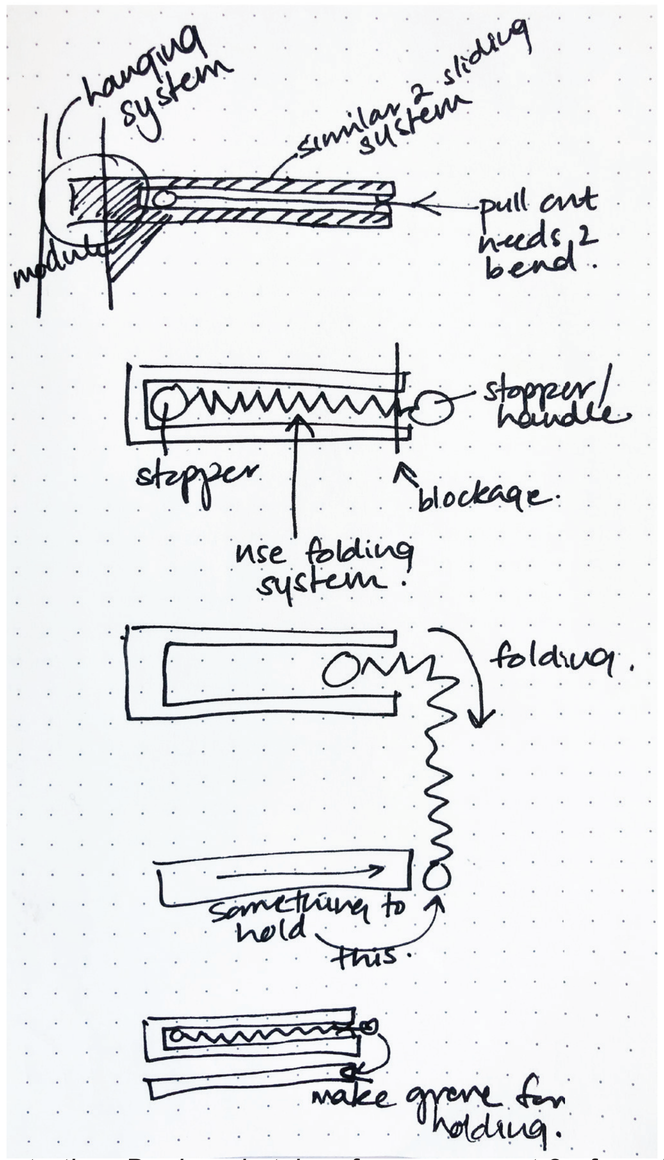


Illustration: Design sketches for component 2 of combination design (Own Illustration)

	Yes	To a certain extent	No
Do the TC's complement the possible fucntion	2	1	0

	Yes	No
Can the component perform more than one function	2	0

	Yes	Not needed by design	No
Can the componnt bare weight	2	2	0

	Yes	Not needed by design	No
Is it possible to adapt the component for a different function	2	2	0

Table: Numeric grading of each different criteria (Own Illustration)

Type/name	Discription	Combination of transformable connections used		Do the TC's complement the possible fucntion	Can the component perform more than one function	Can the componnt bare weight	Is it possible to adapt the component for a different function	Ease of handling	Single person handling	**Success after prototyping**	**Success after testing**	**Total**
Component 1	Flat surface in combination with folding expandable surface	Hanging System + Folding System +Clip system	PROTOTYPE JOINTS	2	2	2	2	2	2	tbp	tbt	12
Component 2	Flat surface with hidden extendable surface	Hanging System + Sliding System + Folding system		2	2	2	2	2	2	2	2	16
Component 3	Flat surface with depression at the end for attachment	Hanging system + Clip System		2	0	2	2	2	2	2	2	14
Component 4	Falt surface with integrated extendable surface	Hanging system + Sliding System		2	2	2	2	2	2	2	2	16
Component 5	Grooved surface with expandability	Hanging system +Clip System + Folding System		2	0	2	2	2	2	tbp	tbt	10
Component 6	Rectangular component with attached wheels	Clip System + (other systems according to function)		2	2	2	2	2	2	tbp	tbt	12

TC = transformable connection

TBP = To be protptyped

TBT= To be tested

Table: Numeric validation of criteria for combination designs(Own Illustration)

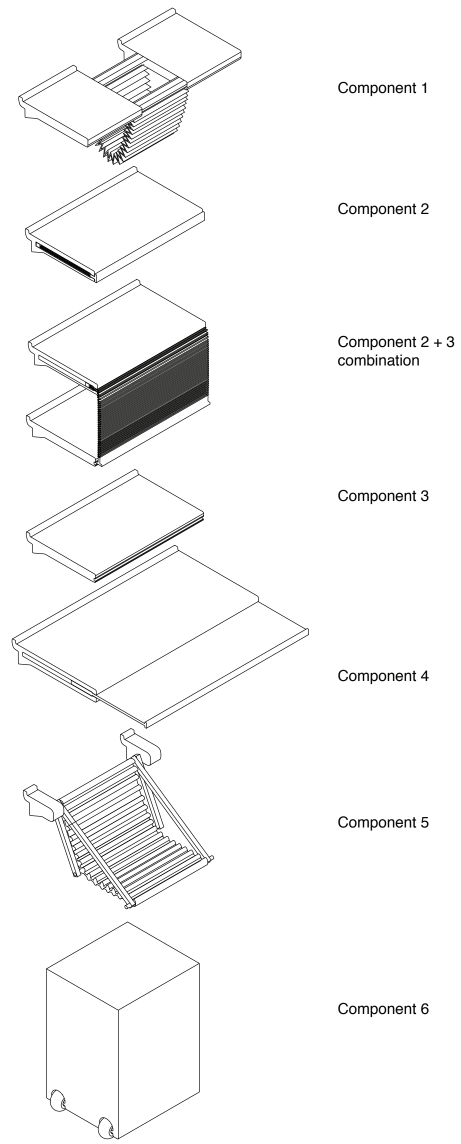


Illustration: Isometric view of all designed components (Own Illustration)

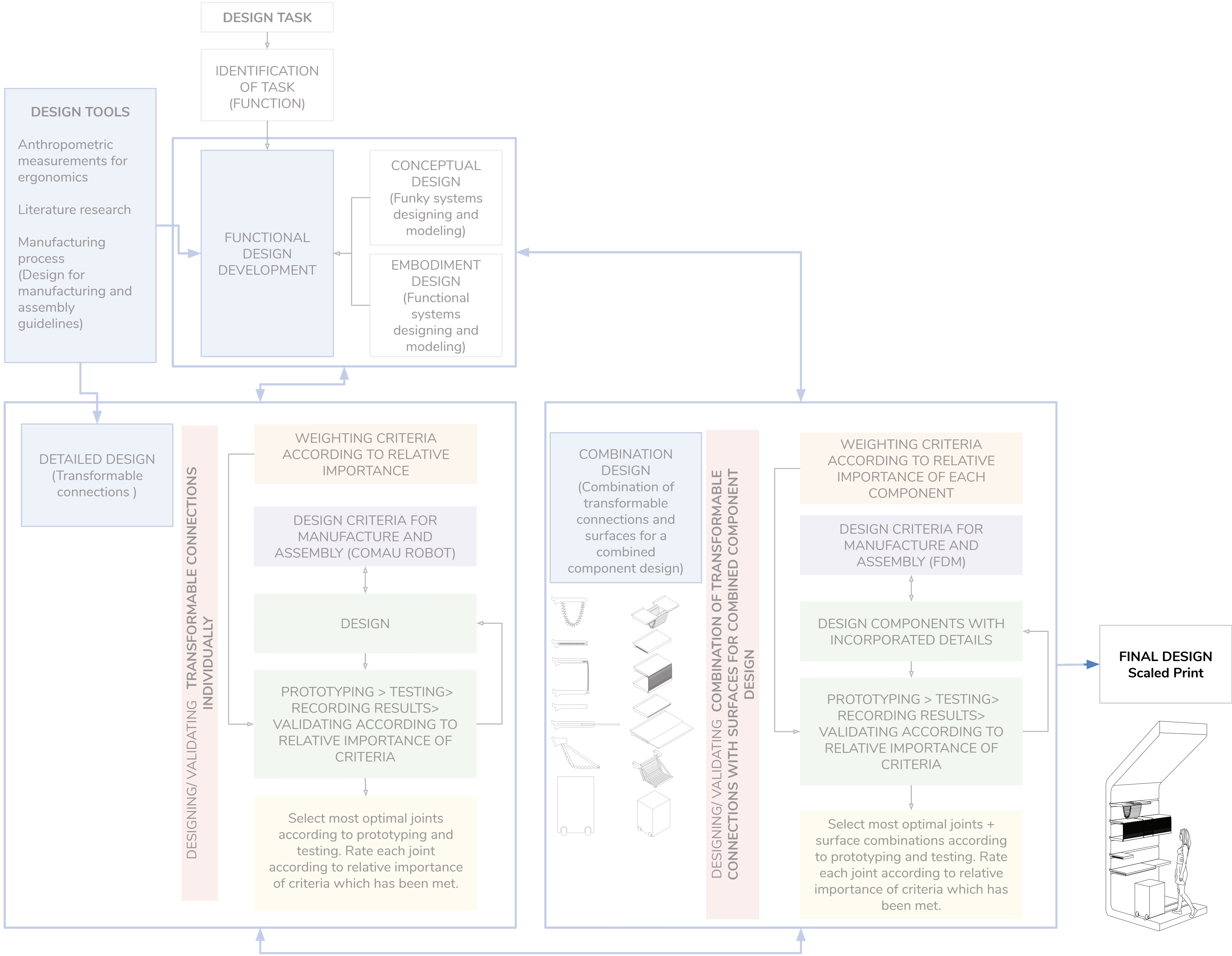
SUMMARY

The combination design phase is a process followed by the detailed designs. Once the derailed designs are validated, and certain transformable connections are tested to be of proper functions, a single transformable connection or multiple can be combined in order to design a component for a particular function. Using the main hanging system as a base to connect each component to the modular wall of the tiny home, the following part of the component can be designed according to various needs. The design may vary according to function, user need or the designer's creativity.

The main goal of the combination design, is to allow any and all users who may have access to a FDM machine and the transformable connections from the 'maker spaces' will have the necessary tools to design their own unique components and print them at the comfort of their own home.

The methodology for designing the combination designs is similar to that of detailed design. However, except for the design criteria for manufacturing, steps such as Weighting criteria and validating the combination designs will vary according to each individual combination design. The criteria used for weighting and validating each component will differ according to each individual design. A single combination design (component 2) has been taken as an example for further explanation through the combination design phase of this design task.

RESEARCH BY DESIGN: FINAL DESIGN



10.1 PROPOSITION OF A MASS CUSTOMIZATION SYSTEM FOR ADDITIVE MANUFACTURING

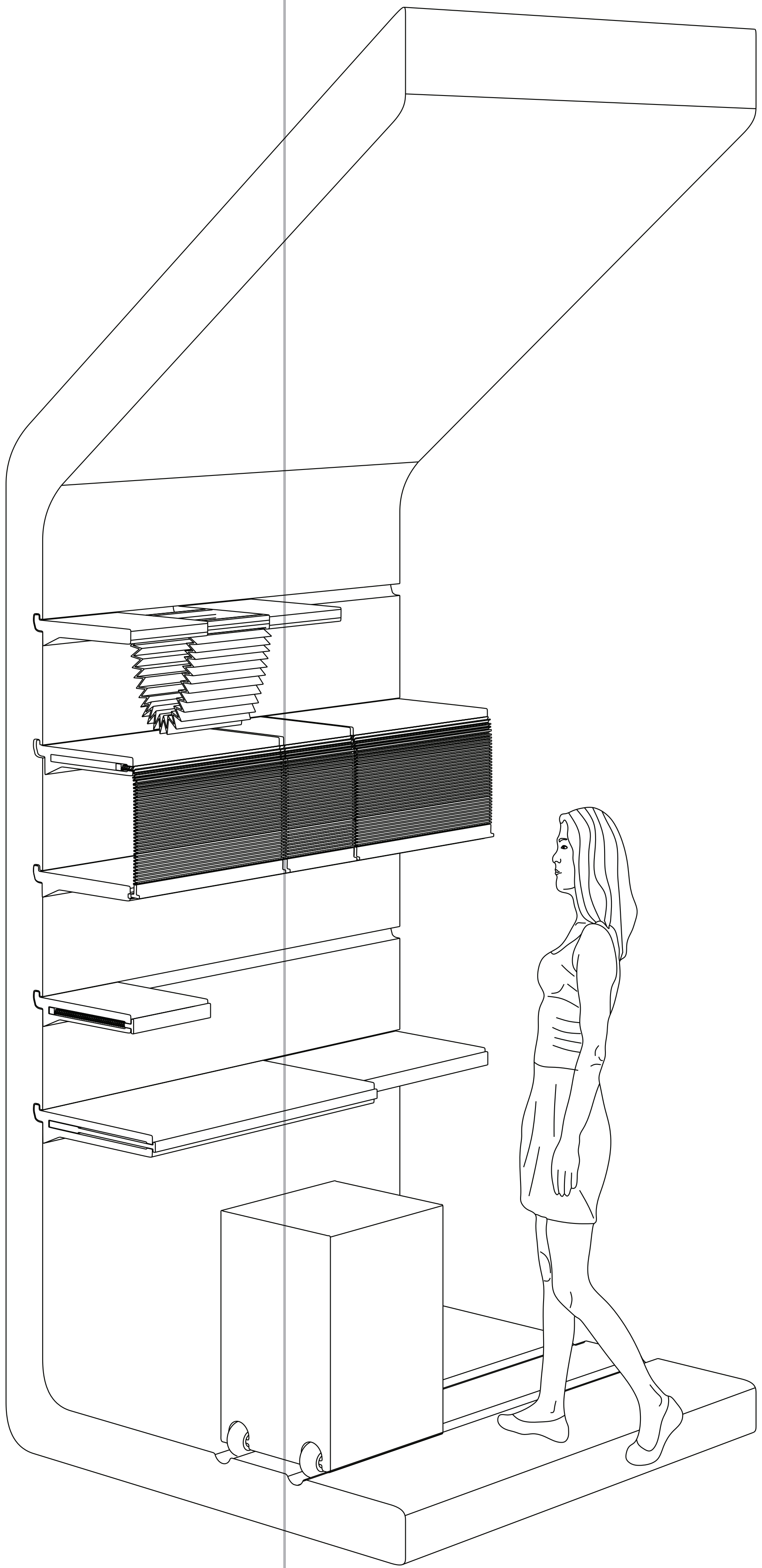
This thesis project is based on additive manufacturing using recycled PET and customization of interior components according to different users and functions. Another strong motive of this thesis is to make the validation methodology and resulting transformable connections available to the masses of makers with access to designing software and a 3D printer (Additive manufacturing machine). The proposed methodology though this thesis studies, in combination with rapid prototyping suggests as an advanced method of trial and error, to be conducted by the user itself rather than traditional methods where a single design team and large scale manufacturers stand in between a single designer and mass production of an object. Therefore giving everyone the opportunity to see through the evolution of their own design with a system in-exclusive to experts.

One of the major drivers of allowing this system to occur is mainly the manufacturing method; Additive manufacturing. The customized methodology combined with the manufacturing method (AM) suggests that the designer itself can also be the manufacturer rather than depending on costly, large scale and traditionally bound manufacturing methods such as extrusion molding. The only variants for additive manufacturing being duration of time, quantity of material and energy supply, other factors such as a third party design and manufacturing team, extra use of support/ scaffolding material and large energy consumption of traditional manufacturing factories can be taken out of the equation for the case of this suggested system for manufacturing.

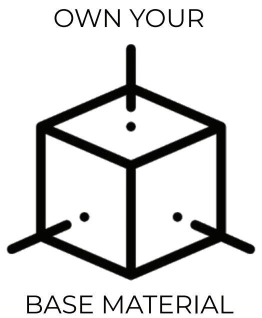
Further, the ease and convenience of rapid prototyping suggests that the evolution of the design does not need predictive modeling whilst it can be prototyped using the same material as used for production and if necessary to be prototyped 1:1. This factor is backed up by the suggestive use of PET as the only manufacturing material for this design task. The use of recycled PET solely allows for the material to be recycled without having to be down-cycled due to chemical recycling (further detail discussed and referenced in the introduction chapter of the report).

The flexibility of using additive manufacturing for rapid prototyping and final design manufacturing gives the designer/manufacturer (both the same in the proposed system for this design task) flexibility in customizing the design as they go and as they see fit for different functions. This thesis suggests a set of standardized transformable connections that have been prototyped, tested and validated. If the designer does not see an ideal set of desirable connections, they may use the methodology and design tools provided through this thesis to design, prototype, test and validate new transformable connections as they please. The proposition of a set of transformable connections in this thesis allows the designer to pick from a base of transformable connections. Therefore the designer is given a set of standard connections, where they have the option to pick the most suitable/ desirable combination, to then design the surfaces in between. Once designed according to criteria set by the designer according to the template of the methodology, they can make quick prototypes, physically test them in the real world and make iterations accordingly. Once satisfied with the performance of the prototypes, the designer can then print a final design accordingly. Therefore suggesting mass customization unconstrained by the possibilities of individual choice; customization for the masses.

The methodology suggested by this thesis could be adapted to many different types of prototypes and objects based on additive manufacturing. The suggestive system for additive manufactured transformable connection based furniture is an engineered system backed by methodology and design tools of customization made available to the masses. Although a system was not the start of this thesis, it has evolved through each process to a system that should be accessible by everyone given the method of manufacturing.



10.2 DESIGN SUMMARY



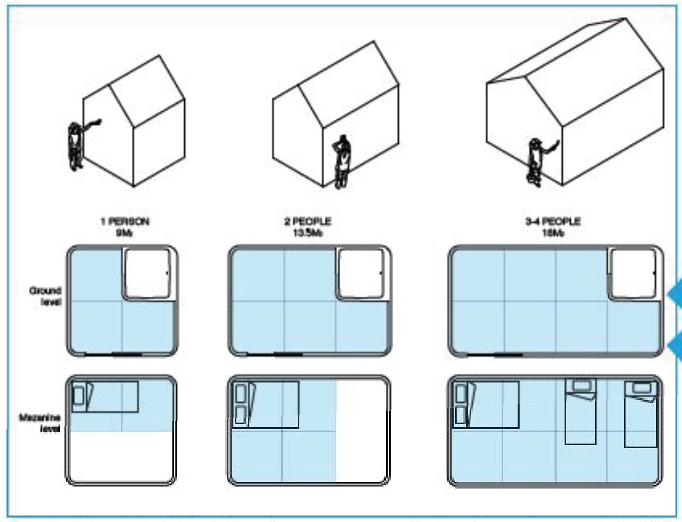


Illustration: Modular tiny house concept developed as context for this design task (Own Illustration)

Illustration: Scheme of three sections of the design (Own Illustration)

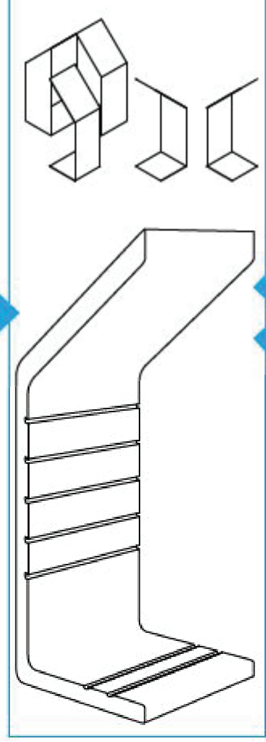


Illustration: Single module of tiny home designed as context for this design task and detail isometric of hanging system integrated to the wall of a single module (Own Illustration)

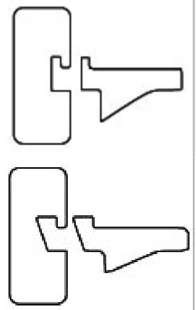


Illustration: Main hanging system for connecting the module with other transformable connections (Own Illustration)

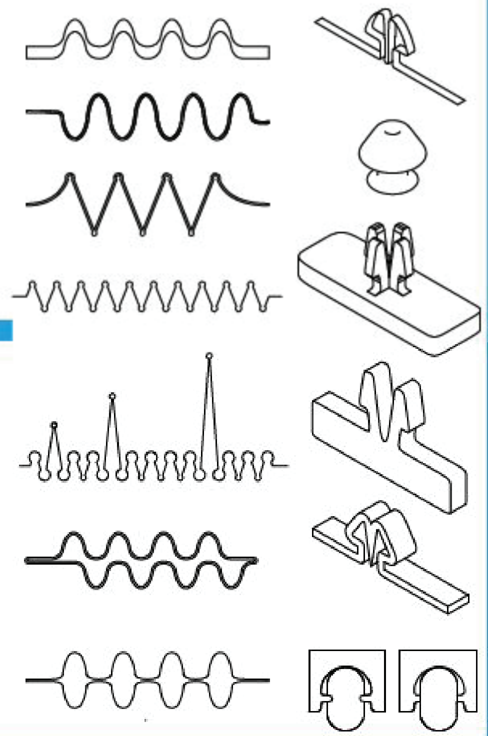


Illustration: Transformbale connections to be combined with the main hanging system for the design of a component (Own Illustration)

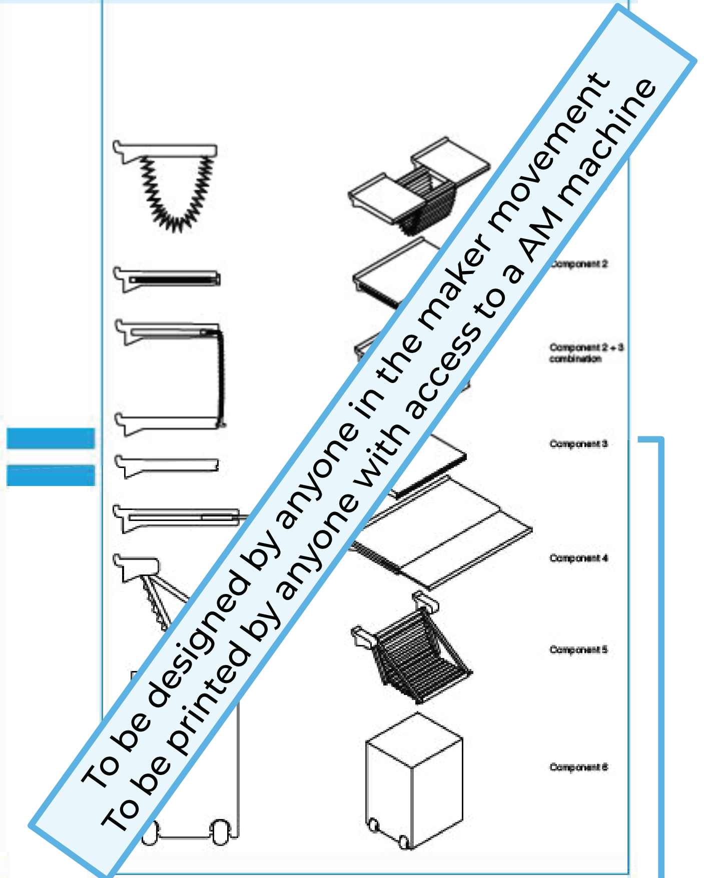


Illustration: Components designed in combination with transformable connections and the main hanging system. More combinations could be according to the need of a certain function by any designer having access to an additive manufacturing machine. (Own Illustration)

REFLECTION

The design task as set out from the start was based on Additive manufacturing of a tiny home using recycled PET. Early on in the stages of this thesis, detailed designs were set to be designed on a smaller scale, validated, prototyped and tested. In order to validate the need to use Additive manufacturing as the main manufacturing method was justified using literature research and basic comparison with other traditional construction methods. The 'Maker movement' dominating the field of additive manufacturing reinforced the possibility for this design task to be made available for anyone with an additive manufacturing machine to build on their own. Rather than having to invest in larger quantities and expensive production methods unable to customize products at a low cost, additive manufacturing allows mass customization in a fast and inexpensive manner at the comfort of your own home.

The evolution of the methodology through the design process lead to a strong focus on making the overall system readily available to the masses. The possibility to make the above system available to the maker movement and to promote individuals to design the evolution of their own design, also became a main driver for the completion of this thesis. Making this thesis available to the masses will create a wide variety of transformable furniture over time. The collection of different transformable furniture then could possibly act as a bank of furniture anyone with access to an additive manufacturing machine could manufacture. The possibility for anyone to design such components, given a standard collection of transformable connections and not needing predictive modeling may seem desirable to the masses.

The process for completing the design task relied heavily on the methodology itself. The lack of availability of methodology for validating additive manufactured products after extensive research proved the need to develop a methodology specific to this design task. Extensive research was conducted into existing and proven methodologies in the fields of additive manufacturing and prototyping as a design tool.

A methodology for this particular design task was developed using some existing methods such as the house of Quality and adapted them to suit the specific needs/ requirements of the expected design process. Prototyping using additive manufacturing techniques for recycled PET was used as a main input / output to the entire design process. Quick prototypes were designed, tested, validated and re-designed when needed in a very circular manner in certain design steps. Constraints for additive manufacturing has strongly influenced the entire design as the design task is meant to be manufactured using this technique.

Planning was done according to the steps of the methodology that outlined each design task/ process. However, as initially suggested, a 1:1 prototype was to be printed using a ComauNJ602.2 printer. This step was eliminated from the methodology due to the closing down of all facilities due to the Corona Virus outbreak. It is possible that later on, if this design task is further studied and researched into, that the 1:1 model will become a reality.

Although each part of the methodology was given a specific time frame, it was evident through the design process that many sections influenced one another in terms of design. This is evidently shown in the slight changes made to the initial design process as described in detail under the 'ADAPTATION' sections. All changes were carefully observed and implemented when seen necessary and was supported by reasoning throughout the methodology section. It is inevitable that certain changes occur when the methodology is being put into practice compared to purely having it theoretically written down. For these changes to occur for the betterment of the methodology, prototyping played a large role in validating all such changes.

To an extent the initial methodology did work, however, necessary changes needed to be made when it was put into real time practice. Theoretically the methodology needed to go through many forms of changes, and with the aid of physical prototyping, the methodology could achieve a final version for this particular design task as shown in this report.

Due to the conceptual design part which influences this design task, many of the criteria considered to be weighed and was guiding the validation process were criteria decided by myself according to certain functional guides of what each component or transformbale connection needed to achieve. These criteria decided by myself or any individual to use this methodology in the future, will however be given the opportunity to grade these personal criteria in a numerical manner. This may allow for cohesion to a certain extent of any and all designs already designed or any and all designs to be designed in the future. This methodology is brought forward to be hopefully further developed and adapted by further studies of the same topic or topics of similar background (Additive manufacturing and prototyping. The methodology is open to interpretation where seen necessary and may indeed differ from one design task to another in the future.
Although a few mishaps did occur due to the corona virus outbreak, in general I believe consistency is key when realizing a project like this. Consistency, prototyping, redesigning and prototyping again were steps that helped mostly for a cohesive development of this design task. However, I believe more prototyping could have been done in a planned manner for further development. It is important to be aware of the changes that occur in the design process over time when put into practice and how the 1:1 prototype, if ever printed will also lead to similar changes to be made in the design process when it is being put into practice.

I believe that this project is a prime example of integrating research into design. From the initial literature review which allowed for a detailed development of the methodology to research into case studies to justify and outline certain details of the design task, research played a main role in this design task. All design steps/ processes had to a certain extent been influenced by the research process and allowed for them to be put to use in real time through prototyping. Although design by research did occur, research by design played a large role toward the middle and to the end of this design task. I believe for a project such as this, a theoretical backing allows for a more guided design process while practical developments such as prototyping allows the project to give back from its design to the field of research itself.

In Terms of the manufacturing method and the use of material; PET after being prototyped and tested prove to be a much stronger material than the idea of it being 'single used plastic'. This proved positive for the structural strength of any of0a the printed prototypes. The manufacturing method which is additive manufacturing reinforced the editing positive material properties of recycled PET with compressing the material strength when printing is denser layers. Overall the possibility of recycling PET without actually down-cycling the material when used by itself is a strong enough reasoning to continue to use this material for more significant uses rather than for single use purposes.

FUTURE RESEARCH

This project could be categorizes as the primary stage of what could become a commonly used design and manufacturing method. Therefore there could be a few more avenues where further research could be conducted;

1. Refine the methodology and design process to a higher level of intricacy
2. Structural tests and validations of the transformable connections and transformable furniture under controlled environments
3. Adapting the design for 1:1 print using a larger scaled printer such as the Comau NJ6 2.2 (available in the LAMA lab TuDelft) (Evaluate the combination of a robotic arm with a high material flow extruder as a possible manufacturing tool.)
4. Research more optimal ways of using the printer and the material.
5. Research more into the system where more components could be designed using different criteria/ approaches
6. Possibility to test out the printing system using other materials.
7. Possible ways to connect the modular living modules together (water tightness, air tightness.
8. Designing the wall of the interior module (possible combination of all services into one wall panel.

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APPENDIX

FORWARD AM
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Technical Data Sheet

Ultrafuse rPET

Date / Revised: 14.11.2019 Version No.: 3.2

General information

Components

Recycled Polyethylene terephthalate based filament for Fused Filament Fabrication.

Product Description

PET is mainly known by the well-known PET bottle material. This recycled has a natural transparent blueish look. It has excellent 3D printing properties and good mechanical characteristics.

Delivery form and warehousing

Ultrafuse rPET filament should be stored at 15 - 25°C in its originally sealed package in a clean and dry environment. If the recommended storage conditions are observed the products will have a minimum shelf life of 12 months.

Product safety

Recommended: Process materials in a well ventilated room, or use professional extraction systems. For further and more detailed information please consult the corresponding material safety data sheets.

Notice

The data contained in this publication are based on our current knowledge and experience. In view of the many factors that may affect processing and application of our product, these data do not relieve processors from carrying out their own investigations and tests; neither do these data imply any guarantee of certain properties, nor the suitability of the product for a specific purpose. Any descriptions, drawings, photographs, data, proportions, weights etc. given herein may change without prior information and do not constitute the agreed contractual quality of the product. It is the responsibility of the recipient of our products to ensure that any proprietary rights and existing laws and legislation are observed.

Technical Data Sheet for Ultrafuse rPET

Version No. 3.2

Recommended 3D-Print processing parameters	
Nozzle Temperature	225 – 245 °C / 437 – 473 °F
Build Chamber Temperature	-
Bed Temperature	65 – 85 °C / 149 – 185 °F
Bed Material	Adhesive spray or glue
Nozzle Diameter	≥ 0.4 mm
Print Speed	30 - 60 mm/s

Drying Recommendations	
Drying recommendations to ensure printability	60 °C in a hot air dryer or vacuum oven for 4 to 16 hours

Please note: To ensure constant material properties the material should always be kept dry.

General Properties		Standard
Printed Part Density	1273 kg/m³ / 79.5 lb/ft³	ISO 1183-1

Thermal Properties		Standard
HDT at 1.8 MPa	65 °C / 149 °F	ISO 75-2
HDT at 0.45 MPa	71 °C / 159 °F	ISO 75-2
Glass Transition Temperature	83 °C / 181 °F	ISO 11357-2
Melt Volume Rate	15.1 cm³/10 min / 0.9 in³/10 min (220 °C, 5 kg)	ISO 1133

Technical Data Sheet for Ultrafuse rPET

Version No. 3.2

Mechanical Properties

Print direction	Standard	XY Flat	XZ On its edge	ZX Upright
Tensile strength	ISO 527	38.6 MPa / 2.4 ksi	-	14.7 MPa / 0.9 ksi
Elongation at Break	ISO 527	4.3 %	-	1.2 %
Young's Modulus	ISO 527	1640 MPa / 100 ksi	-	1334 MPa / 81.4 ksi
Flexural Strength	ISO 178	66.9 MPa / 4.1 ksi	65.4 MPa / 4.0 ksi	30.2 MPa / 1.8 ksi
Flexural Modulus	ISO 178	1662 MPa / 101 ksi	1551 MPa / 97.6 ksi	829 MPa / 50.6 ksi
Flexural Strain at Break	ISO 178	5.5 %	4.8 %	3.0 %
Impact Strength Charpy (notched)	ISO 179-2	4.0 kJ/m²	2.0 kJ/m²	1.0 kJ/m²
Impact Strength Charpy (unnotched)	ISO 179-2	55.5 kJ/m²	33.7 kJ/m²	3.3 kJ/m²
Impact Strength Izod (notched)	ISO 180	4.4 kJ/m²	3.3 kJ/m²	1.5 kJ/m²
Impact Strength Izod (unnotched)	ISO 180	48.2 kJ/m²	21.9 kJ/m²	4.4 kJ/m²

APPENDIX II : OLD METHODOLOGY PRE ADAPTATION

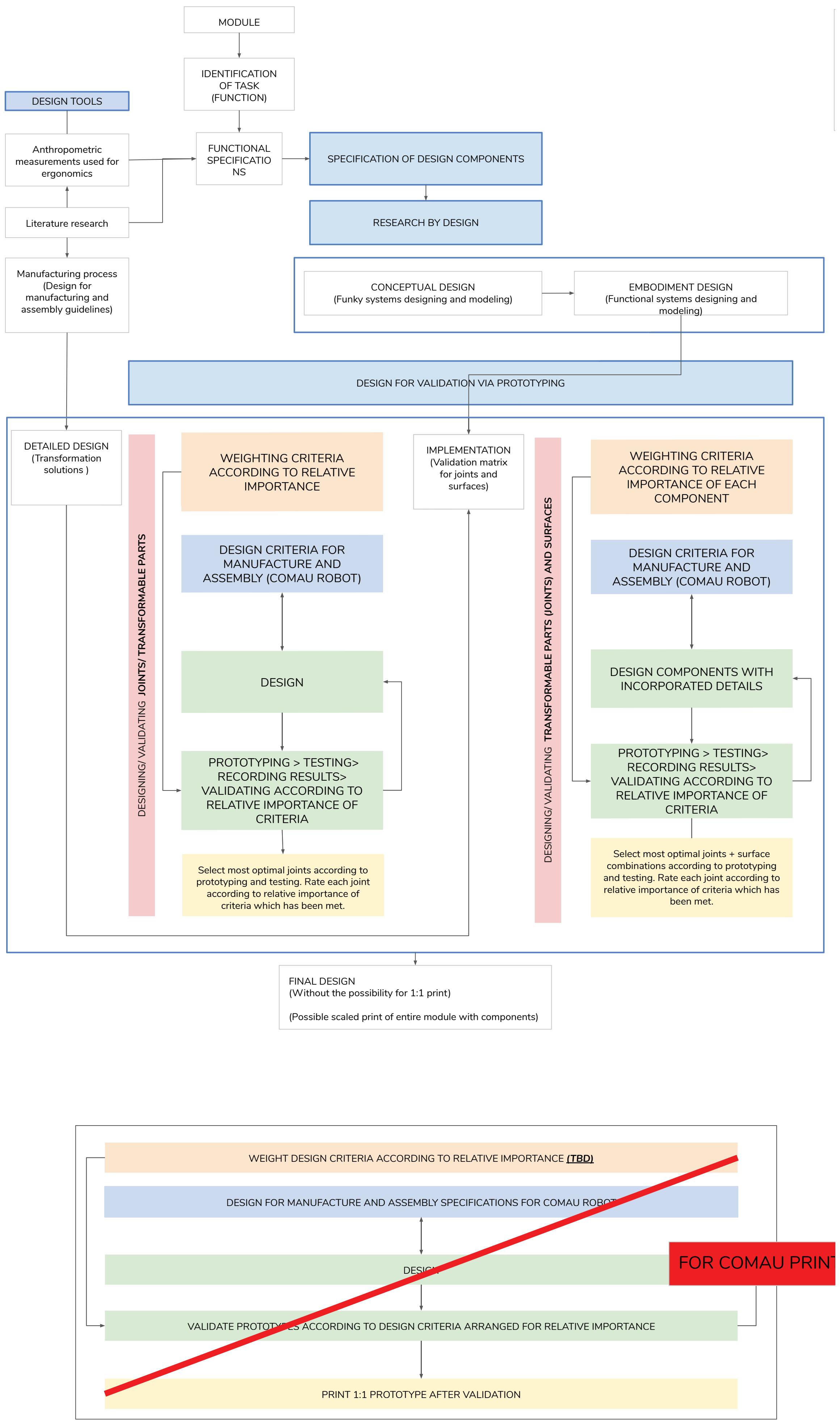


Image : Suggested methodology summarized (Own illustration)

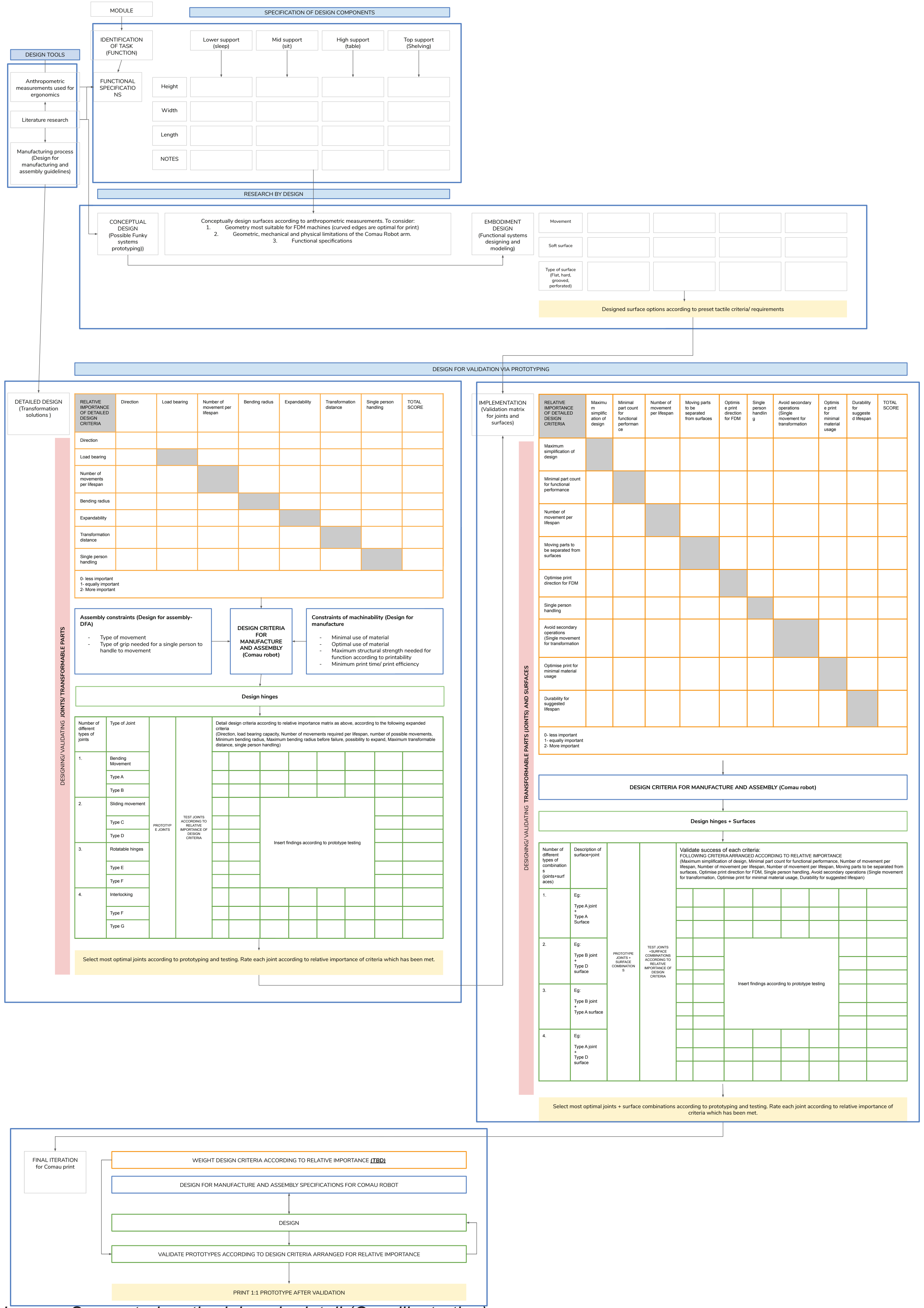
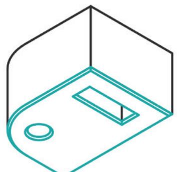


Image : Suggested methodology in detail (Own illustration)

GENERAL CRITERIA TO BE CONSIDERED WHEN DESIGNING FOR ADDITIVE MANUFACTURING



BASE CHAMFERS

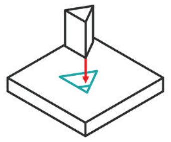
Recommended Value: ~0.3 mm (initial layer height + layer height)

To improve the accuracy of the base edges of your part, it is a good idea to add a small chamfer of ~0.3 mm to all the edges that will be in contact with the print surface. This will reduce the chance of a slightly over "squished" first layer creating a lip around the base of the part.

BRIDGING

Recommended Value: <10 mm

Horizontal bridges without support should not be longer than 10 mm to avoid print defects and failures. Either build vertical structures into your model to support the bridge or enable printed supports during slicing. You may find that you can bridge much larger gaps depending on the material and layer height, but keeping bridges <10 mm is a good starting point.



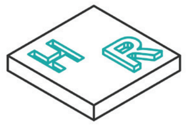
CLEARANCE

Recommended Value: ~0.3 mm for loose fit ~0.15 mm for tight fit

When 3D printed parts will fit together, a clearance of ~0.3 mm for loose fit and ~0.15 mm for tight fit mm is recommended to ensure a good fit. The required clearance may vary slightly depending on material and geometry.

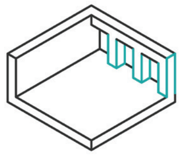
EMBOSS & ENGRAVE HORIZONTAL

Recommended Value Emboss: >0.9 mm wide (2 times extrusion line width) <0.9 mm (2 times extrusion line width) out
Recommended Value Engrave: >0.5 mm wide x <0.9 mm deep (2 times extrusion line width)
To ensure embossed or engraved details on a vertical surface are resolved and visible, the line width should be at least twice your nozzle diameter in depth. They can be a little bit larger, but will start to sag if they are too big.



EMBOSS AND ENGRAVE VERTICAL

Recommended Value Emboss: >0.9 mm wide (2 times extrusion line width) x <2 mm high
Recommended Value Engrave: >0.5 mm wide x <2 mm deep
To ensure embossed or engraved details on a horizontal surface are resolved the line width should be at least 0.5 mm wide for engraving and 0.9 mm wide for embossing. There is no limit on the height of the details, but modeling them 2 mm high will make the features clearly visible.



FEATURE SIZE

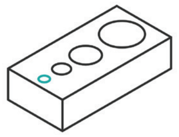
Recommended Value: >1.8 mm or 4 times extrusion line width

The minimum feature size for printed structures is 4 times your extrusion line width. A good rule of thumb for general modeling is making features no smaller than 1.8 mm.

FILLETS

Recommended Value: > ø1 mm, do not use downward facing fillets

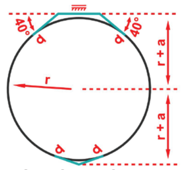
It is not recommended to model downward facing fillets on 3D printed parts. Chamfers area a good alternative for downward facing edges that you may wish to soften. Downward facing fillets will not cause your print to fail, but that may come out with poor aesthetic/surface quality.



HOLE SIZE

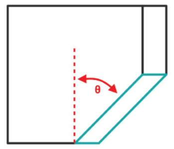
Recommended Value: > ø2 mm

It is not recommended to model holes with a diameter of less than 2 mm to ensure they are resolved. If an accurately sized hole of any size is necessary, under-size the hole and drill it out to the proper tolerance.



HOLES HORIZONTAL

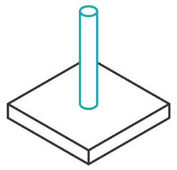
Recommended Value: a ≈ 0.3 mm
In order to print horizontal holes with a better tolerance, it is recommended to model the additional features in the image where the offset distance a, is the layer height of your print. If you are using a small layer height like 100µm you should do 2*a. This will accommodate for any drooping that will occur in the steep overhang sections of printed horizontal holes and the "flattening" of the bottom of holes due to the stacked layer process.



OVERHANGS

Recommended Value: < 50°

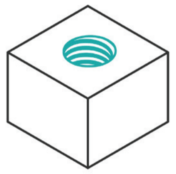
To prevent layers from drooping or curling on printed overhangs, it is recommended to avoid printing unsupported overhangs at angles less than 50° (measured from the vertical axis down). Overhang quality can also be material dependent, so some materials may require support at lower angles than others.



PINS

Recommended Value: > ø1.8 mm (4 times extrusion line width)

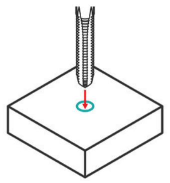
In order to accurately resolve pins, their diameter should be at least four times the extrusion line width to ensure at least two full perimeters are printed, a good rule of thumb is ø1.8 mm. If functional pins are required in your model, it may be better to use store bought pins and model holes into both sides of the joint.



THREADS MODELED

Recommended Value: > M5 or UNC #10

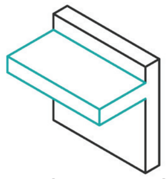
3D printing modeled threads can work well for larger thread sizes. It is not recommended to model threads smaller than M5 or #10 so that they will function effectively. If you need threads smaller than M5 or #10, they should be added with post-processing techniques. DO NOT use modeled/printed threads for horizontal holes.



THREADS POST-PROCESS

Recommended Value: Tap: 90%, Self-Tap: 96%, Insert: 98%

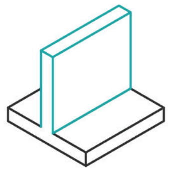
Threads can be added in post-processing a few different ways. You can thread tap the hole, in which case model the hole at 90% of the thread diameter. You can self-tap the screw into un threaded hole, in which case model the hole at 96% of the thread diameter. You can also use heat-set inserts, in which case model the hole at 98% of the inserts outer diameter.



UNSUPPORTED EDGES

Recommended Value: < 0.9 mm (2 times extrusion line width)

It is generally recommended to avoid printing unsupported, horizontal structures that are more than two extrusion line widths wide, a good rule of thumb is 0.9 mm. It is unlikely that larger unsupported edges will cause print failures, but they will cause serious cosmetic issues. If the structures are necessary for your model, altering print orientation and/ or enabling supports will make them printable.



WALL THICKNESS

Recommended Value: > 0.9 mm (2 times extrusion line width)

It is strongly recommended to model walls at least two extrusions wide, generally this will be 0.9 mm. Thinner walls can have issues printing successfully and will not be very strong. Perimeters are the greatest source of strength in a 3D printed part, so if strength is important it is recommended to make walls more than two perimeters thick. Increasing perimeters will need adjustments in both modeling and slicing.

Information and illustrations: HydraResearch3d.com/design-rules

TRANSFORMABLE CONNECTION 1: BENDING SYSTEM

The following system was based on the following requirements;

1. Possibility to move in a single direction when transforming
2. Have a bending radius of 45 < in order to successfully transform
3. Possibility to expand as a result of transforming
4. Ability for a single person to handle the transformation
5. Be able to transform to a maximum degree (2) without failure
6. Have the ability to transform to a maximum amount of its life span (maximum amount of movements per life span depends on the extended function adapted by the designer.)

The following diagram shows the grading of Primary criteria to be considered when designing the bending system. The grading system is based on the development of the conceptual design based on ergonomic measurements of the human body. Once the transformable connections were conceptually developed, specific criteria became of more importance than the other. Therefore in order to validate and justify the most important criteria, the primary criteria considered will be graded against the criteria to be considered. A grading system of 0= less important, 1= equally important, 2= more important will be used.

Once graded, all criteria below the score of 5 were not taken into consideration given that the other with a higher score had a higher importance in the design. Accordingly, the following designs were digitally designed for the FDM process. The below profiles were printed each and tested based on function in a smaller scale.

Further illustrated, the 7 profiles designed, and tested according to a set of criteria they were designed based on. Once these designs were prototyped, they were tested as shown below using a second validation methodology.

Appendix IIII

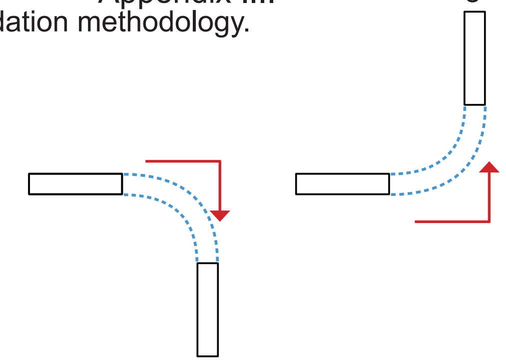


Illustration: Scheme for folding system

TRANSFORMABLE CONNECTION 2: SLIDING SYSTEM

The following system was based on the following requirements;

1. Possibility to move in a parallel direction when transforming as a connection
2. Ease of handling for a single person when transforming
3. Possibility to bear load pre and post-transformation
4. Possibility to extend a maximum amount of times necessary before failure**
5. Have the ability to transform to a maximum amount of its life span (maximum amount of movements per life span depends on the extended function adapted by the designer.)

**further testing for validation of 'maximum number of movement' needs to be conducted in a controlled environment

According to the above requirements and functional requirements, the sliding movement could be divided into two main categories;

1. Purely for the purpose of extension and load-bearing after transforming as a connection
2. As an extension that can fold and 'cover' the objects below or above after transforming as a connection

Both systems can be incorporated into different aspects of design as seen necessary. The sliding system allows for flexibility within functions and added space when stowed away. Below is a detailed description of the grading process for design criteria to be considered. In order to validate and justify the most important criteria, the primary criteria considered will be graded against the criteria to be considered. A grading system of 0= less important, 1= equally important, 2= more important will be used.

Following page shows the two tested transformable connections, Profile 1 possibly to fold while profile 2 designed to have structural integrity in supporting its own load and load distributed on top of the extension when in use.

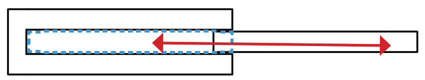


Illustration: Scheme for folding system

TRANSFORMABLE CONNECTION 3: CLIP SYSTEM

The following system was based on the following requirements;

1. Single person handling when transforming as a connection
2. Possibility to transform to a necessary amount of times as needed in its life span
3. Maximum Number of movements as required before failure
4. Have a substantial bending radius for the connection to transform
5. Possibility to bare load before and after transforming as a connection

According to the above requirements two types of transformable connections, essentially with the same functional principle will be designed as follows;

A clip system to connect two surfaces together
A clip system to hold wheels in place

Five clip systems were prototyped and tested in order to assess functionality. The 6th system was designed purely for the functional purpose of holding a spherical object in place. These designs are represented in the illustration below.

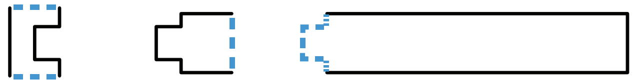


Illustration: Scheme of three sections of the design (Own Illustration)

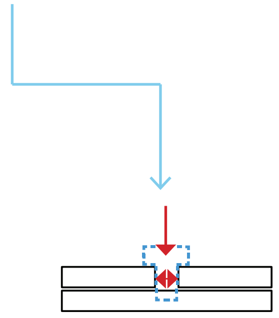


Illustration: Scheme for folding system

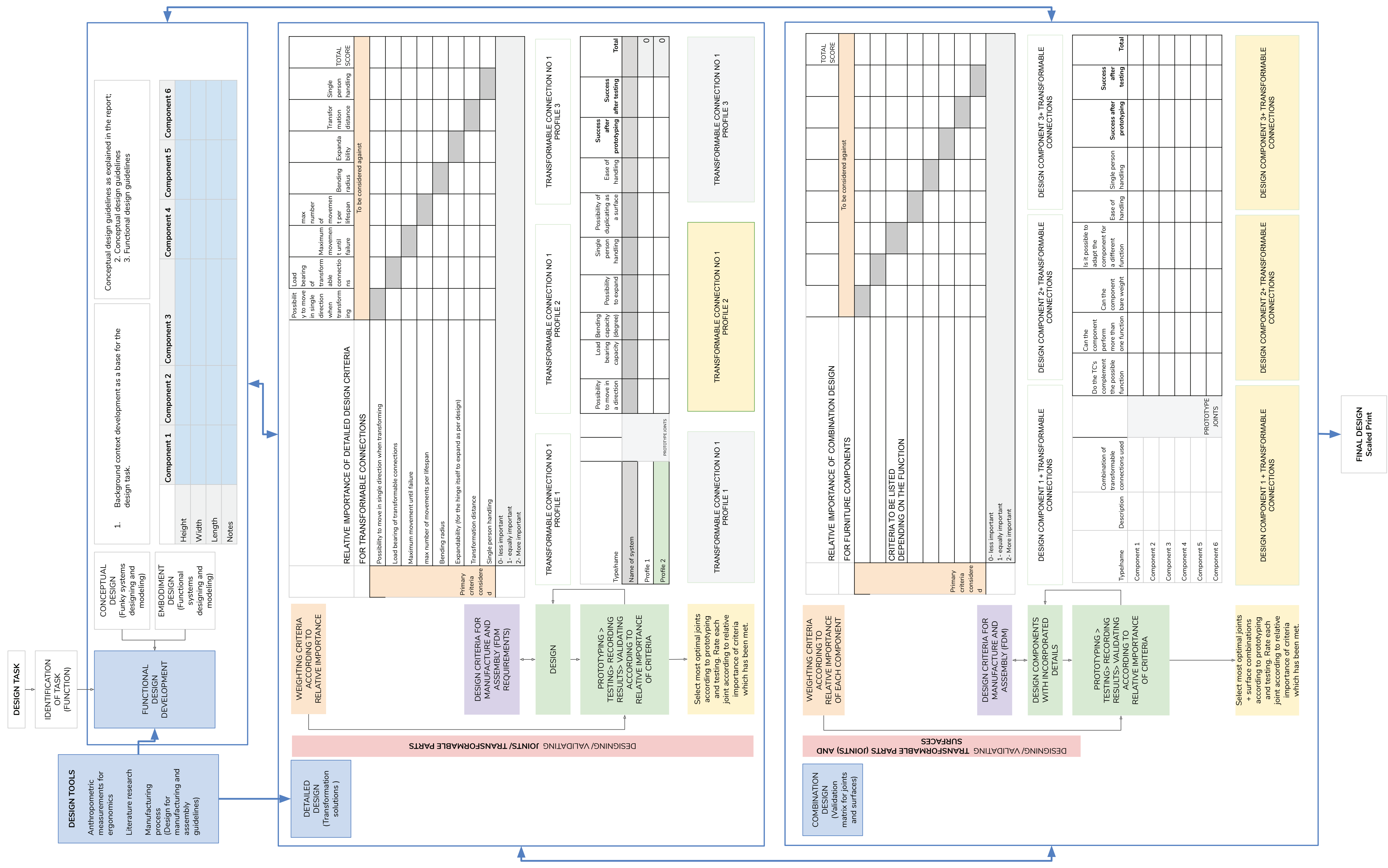


Image : Adapted methodology in detail (Own illustration)