Generative Design for Agile Robot Based Additive Manufacturing for Sustainable Aesthetic Furniture Products

A Thesis Submitted for the Degree of Doctor of Philosophy

In

Design for Sustainable Manufacturing

Andrew Richard Fox

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Department of Design

College of Engineering, Design & Physical Sciences

Brunel University London

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Abstract— The Furniture manufacturing industry has been slow to adopt the latest manufacturing technologies, relying heavily upon specialised conventional machinery. This approach not only requires high levels of specialist knowledge, training and capital investment, but also suffers from significant traditional subtractive manufacturing waste and high logistics costs due to centralised manufacturing, with high levels of furniture product not re-cycled or re-used at the end of its life cycle. This doctoral research aims to address these problems by establishing a suitable digital manufacturing technology framework concept to create step changes in the furniture design to manufacturing pathway. The design stage has the potential to contribute massively to the environmental impact of products. In this research, a Robot Base Additive Manufacturing Concept cell for future furniture manufacturing is reported. Generative design illustrates its potential contribution to waste reduction, increased manufacturing efficiency, optimised product performance and reduced environmental impact constituting a truly lean and progressive future for Furniture Manufacturing Design. Through case studies the research will show the potential for exploiting Single Minute Exchange of Die (SMED) concepts through the rule-based AI generative design post-processing of geometry for robot manufacturing, examination of different methodologies for printing and thus the resultant potential for 'Mass Customised' Furniture. Aesthetics, structures and the use of Smart Materials not previously economic to manufacture will be considered to demonstrate the potential to flatten the traditional Bill of Materials (BOM) and reduce logistical issues.

The Furniture Industry has developed from an artisan driven craft industry, whose pioneers saw themselves reflected in their crafts and cherished the sense of pride in the originality of their designs, now largely re-configured to an anonymous collective mass output. Digital technologies and smart materials enhancement allow innovative structural fabrication, presenting a plethora of potential for networked artisan craft industries to create extraordinary aesthetics and customisable product designs. Integrating these developments with the computing power of generative design provides the tools for practitioners to create concepts which are well beyond the insight of even the most consummate traditional designers. This framework is becoming an active area of research for application in many different industries. The step changes are empowering artisans to revolutionise the design to manufacture workflow, giving momentum to the concept of conceiving a pre-industrial model of manufacturing with bespoke sustainable design at its heart. The elements of the framework will be described and illustrated using case study models highlighting the potential for creating unique aesthetics for sustainable furniture products. The research presents the methodology to create and compare iterations employing different rule sets through a commercial generative design application and how these outputs can be further customised using parametric strategies in NURBS modellers, with the ultimate goal of creating aesthetic 'Lean' and sustainable innovative furniture of the future, thus illustrating how the creative use of digital networks in linking individual practitioners in the making of aesthetic customised products, manufactured local to their markets, could be achieved using this framework.

This research shows a robust 'green revolution' is evidently necessary to satisfy the needs of an ever-growing population, allowing the world to thrive within the means of this planet. New approaches to the use of technologies can achieve these changes in Furniture Manufacturing and establish a truly enhanced Circular Economy. Governments around the World are encouraging these initiatives and these approaches are identified and rationalised alongside the drivers for change which will have major impacts on this manufacturing sector.

This research critically examines the Furniture Design and Manufacturing technologies presented through a TRIZ framework against the desired outcomes. Using this approach together with the physical development of a robotic test cell, combined with case study data significant contributions to knowledge in the focused area of Furniture Manufacturing are identified, detailed and enhance Furniture Design, Manufacturing and Environmental Impact for the future. The focused approach also serves to highlight areas requiring further research.

1 Chapter 1 Introduction

The Furniture Industry with a legacy of significant subtractive manufacturing waste and high logistics costs due to centralised manufacturing, with high levels of furniture product not re-cycled or re-used has a great potential for improvements in process. The Royal Society of Arts (RSA) records that more than 600,000 tons of furniture per annum are disposed of in the UK and only 34% of which is recycled in any way.

This doctoral research aims to address the problems inherent in Design, Manufacturing and Environmental practices by stepping outside of commercial constraints and introducing appropriate digital manufacturing technologies to create step changes in furniture design & manufacture, since it is estimated that 80% of environmental impact is built in at the design stage.

The research will carry out critical thematic literature review and examine multifaceted and interlinked influences, including:

- Environmental mega trends and legislation.
- Smart material design for sustainable products using digital technologies.
- Additive manufacturing technologies and their scaled manufacturing potentials.
- Generative Design of sustainable 'mass customisable' furniture product concepts using Robot Based Additive Manufacturing (RBAM)

Illustration of the problems will be based on TRIZ and will be used to critically examine and resolve issues and conflicts, developing new approaches to digital furniture design and manufacture. The solutions identified will then be simulated & critically evaluated.

The impact of this research will be to demonstrate a sound methodology and practical solutions to the challenges of future sustainable furniture design & manufacturing with goals to reduce waste and significantly increase reuse and recycling of furniture, thus contributing to the development of a circular economy within this sector.

1.1. Problem Statement and Research Background

1.1.1. Background

The Global Furniture Industry is made up largely of SME manufacturers; it is quite a significant industry with a projected turnover of approx. $285,701m in 2022, with China predicted to have a major share of this output projected to be circa. $70,000m in 2022. Its products are extremely end-user focused and are an important product category with which human beings interact for a significant amount of time across many different activities.

In Context the UK Furniture Industry has a total manufacturing turnover of circa. £9.4b with 8114 companies employing 115,000 persons in the UK. The industry is dominated by Micro and SME businesses, with only 260 companies having turnovers more than £5 million (FIRA Statistical Analysis, 2013)

The Furniture Industry is one of the largest mass production industries throughout the world. Design and manufacturing of both functional and decorative products for households and businesses are its major activities. Production of furniture is very specific and is aimed at a mass consumer market. It is extremely design led often containing elements of handwork which are quite opposed to the basic concept of volume production.

Many products especially those in the higher price brackets can be linked with the making of artistic creations. Traditionally this has required a large number of highly skilled craftsmen to produce the aesthetic and more artistic elements of the products. This is especially so in the production of solid wood furniture. The main reason for the high cost of such products is the inability to easily change mass production equipment to achieve the variety of final product designs. Despite the application of approaches such as Single Minute Exchange of Die (SMED) Methodology, the introduction of Computer Numerical Control (CNC), Computer Aided Design (CAD) and the application of One-Piece Flow this remains an issue in creating the required variety for a mass customised product.

The influencers whether they be industrial, consumers or governments are not as important as the core reasons for the change. The Environment influences peoples' health, which in turn has an effect on the Economy. Use of renewables and the development of technologies which assist our ability to sustain enough energy and resources to make our society and economy work. All these individual drivers come together with a common thread being Environment Conservation.

Even though globally the Furniture Industry is a minor contributor it is still vitally important to make substantial changes in all industrial sectors. Development of a Sustainable Manufacturing Strategy for SME Furniture Manufacturing Companies is essential as it is 'The Right Thing to Do' for our planet.

1.1.2. Research Content

The industry is very traditionally based and has grown largely from family-owned small businesses to SME scale and above. Traditional construction techniques are largely employed in the timber sector of the industry i.e. Dowels, Mortice & Tenon, Dovetails, Having joints etc. Many of these traditional jointing approaches do not encourage the recovery, reuse or recycling of product materials at the end of their lifecycle. Knock Down (K.D.) Fittings have started to become more popular especially in the flat pack sectors of the industry, which uses predominantly man-made board materials.

Metals, plastics and other materials tend not to be recycled extensively in this industry and virgin materials are predominantly used in production.

Currently the split of manufacturing costs is estimated to be on average:

- 40% of costs raw materials
- 30% of costs energy / water
- 30% of costs Labour

(Greennovatel, 2012)

In some cases logistics costs may make up to 5% of the total product cost as the finished assembled products are very expensive to transport (FIRA Statistical Analysis, 2013).

The products are largely assembled and constructed using a range of standard materials that contribute significantly to Volatile Organic Compound (VOC) and other emissions. The problem of emissions is controlled to some degree in the UK, but some overseas countries have very few controls in place for their Workforces or the Environment.

Some typical materials are:

- Poly Vinyl Acetate/ Urea Formaldehyde / Phenolic Resin/Contact adhesives/ Hotmelt adhesives
- Polyurethane finishes (Isocyanate Catalysed)
- Pre- Catalysed and Acid Catalysed finishes
- Spirit and Naphtha based stains
- Formaldehyde emissions from board materials
- Degreasing & Powder Coating of metal components

The surface finishing of a product is still largely VOC based (standard and compliant formulations) with some minor movement towards water-based finishes by larger manufacturers. The reluctance to adopt water-based finishes is largely due to increased processing difficulties, skill requirements and increased curing times.

Traditional UK based Design Education for the Furniture Sector has been largely focused on form, ergonomics & aesthetics. Many Furniture Design Graduates and Postgraduates have only a superficial understanding of Manufacturing Technology and Production Economics.

The relatively slow adoption of CAD, CAM and CIM applications are bridging that gap to some degree, but its adoption tends to be very company specific. There are no real standards in the Furniture Industry which makes the sharing of information and design data very difficult between organisations.

In my experience a wide variety of software packages are currently being used in the Furniture, including, but not limited to:

AutoCAD
Inventor
AlphaCAM
Cabinet Vision
Master Cabinet
Magicut
Solidworks

There is a view in many small factories that what they are doing is unique and, in some way, special. There is also an underlying feeling by many furniture manufacturers that Furniture Making is totally different from engineering and the same approaches to manufacturing cannot be used.

Following 37 years' experience and exposure to many different manufacturing organisations in the Furniture Industry, both in the UK and Overseas, I have observed that most employ very similar approaches. It is the exception where one encounters a truly unique method or approach.

There is great potential for savings generally across manufacturing industry, these are suggested to be:

Resource efficiencies savings possible for UK 23bn – 33bn ……. £19000 - £52000 per company per annum (EIO,2012).

Potential areas to develop when examining the 'Leagile' and Environmental aspects of furniture manufacturing may be:

- The use of emerging technologies to influence and change the ways in which Furniture Products are designed and manufactured in the future.
    - Industrie 4.0
- Development of alternative methods of production not currently exploited e.g. Compression bending of timber sections
- Exploring new forms and functionality
    - Adding variety while increasing standardisation
    - Multi-configured and multifunctional furniture
    - Smart Materials and products
    - Furniture without form
        - Electronic e.g., hologram with forces, magnetic etc.
        - Liquids – water beds etc.
        - Gels, waxes & plastics – melt, reform or recycle
    - Growing Furniture Forms
        - "growing furniture isn't going to save the planet, but it can show that it's possible to create genuinely useful things without adding to the pollution that industry inevitably seems to produce. Trees

> are self-generating, and the only energy needed is that which the sun provides worldwide. It's free and it's non- polluting."
> (Cattle.C., GrownUp Furniture)

1.1.3 Problem Statement and Significance

This research, informed by the Literature Review, involves the identification of a novel decision-making framework for application to future UK Furniture Design and Manufacturing Sector in order to fully leverage the potential of disruptive technologies to greatly enhance the efficiency of the design process to enhance product quality, right first time manufacturing and its subsequent sustainable manufacture, with the long term aim to achieve a net zero circular furniture manufacturing environment. The key areas of focus are Robot Based Additive Manufacturing (RBAM), Generative Product Design methodologies and subsequent assessment and modification of process through the use of Life Cycle Analysis (LCA).

Climate change is becoming a key concern of governments and manufacturing sector alike. The result of sluggish changes to traditional practices can be seen first-hand borne out in extreme weather events, drought, flooding, waste pollution and other natural phenomena. The significance of this research is fundamental to rectifying those issues and for the UK Furniture Industry to demonstrate its willingness to explore new avenues for Design and Manufacture that will better fit the global social requirements for a sustainable future. This approach needs also to be echoed in other industrial sectors, as we need to start thinking 'Out of the Box'

1.2 Context for the demonstration of the methodologies

The research will be undertaken using a thematic approach examining the key issues, themes and debates surrounding the development of smart interactive furniture products using sustainable Additive Manufacturing processes and materials.

Novel Solutions will be designed, manufactured and evaluated in digital & scale form. This decision was to make the research feasible from a financial perspective.

To achieve this unique contribution, it will be necessary to set the research within the context of a limited market segment. This will reduce complexity and demonstrate 'The

Framework' within the four-year allowable timescale, producing unique contributions which are easily assimilated and extended into concomitant disciplines.

The intention is to develop unique 'Aesthetic Furniture Forms' utilising 'Smart process Functionality', achieved using innovative sustainable manufacturing processes, smart software solutions and hardware interfacing. This will be illustrated using a problem-solving framework, based on TRIZ, combined with complimentary business and process considerations from DFSS and other approaches. Central to the research ethos is the practical creation of virtual and physical artefacts to evaluate first-hand the performance of the concepts developed. The establishment of novel products & process developments that have the potential to create 'Step Changes'. They may not be recognised through the 'Voice of the Customer' but may become apparent through specialist knowledge and leveraging the 'Voice of the Product'.

In my experience a 'Gap in Knowledge' exists surrounding the transition of Additive Manufacturing from prototyping to a full manufacturing technology. Knowledge Gaps exist in the UK for the development of furniture products which are interactive & sustainable using digital manufacturing technologies and smart materials as the basis for their manufacture.

The development of the TRIZ based 'hybrid' problem solving methodology easily used by SME's will be invaluable in evolving Additive Manufacturing from a prototyping technology to a manufacturing application. The framework should promote both unconstrained creative design potential and the need to manage process and environmental efficiencies.

The research integrates complimentary elements from a number of existing methodologies, all of which have their own strengths and weaknesses.

The methodologies include elements of some of the following:

- De-materialisation
- Jidoka (Autonomation)
- Kaizen (Continuous Improvement)
- Kanban (Just In Time)
- Lean Manufacturing
- Poke Yoke (Error Proofing)

- Pre-Fabrication
- Resource Efficiency
- Six Sigma
- TRIZ
- Optimised Production Technology (Drum , Buffer & Rope)

The research will examine the strengths and weaknesses of technologies and applications with a view to achieving enhanced Sustainable Furniture Manufacturing.

Initial constraints include the following:

- Speed
- Slicing vs freeform print paths
- Creating load bearing structures with 5D (composites)
- Interactive Materials (4D)
- Print Capacity
- Supports and post processing
- Integration with digital design techniques to contract development lead times, repetition & ability to create true mass customised products

Other drivers are also influential, for example:

- Regenerative or recycled material usage
- Development of products that can be preserved and extended with 2nd life
- Identifications of wastage that can be converted to a resource (TRIZ)
- Identification of ways in which the technologies and materials can benefit future business models

- Incorporation of systemic perspective into the Design Process
    - Appropriate materials for lifetime and extension
- Incorporate rational integrated digital technologies into the generative design of furniture
- Examine the potential benefits of the developments to supply chain and logistics.
- Extension of trends towards 'Prosumption' through digital technologies

Due to the time constraints of the research period, the following limitations or project scope will be applied to the research and these will limit the complexity, but give sufficient detail with which to demonstrate the unique contributions derived from the methodologies.

The following limitations (project scope) have been set initially. The study will be undertaken within the following parameters:

- Product class limitation
    - Seating Product
        - Encompasses many of the skill sets and technologies inherent in furniture making
        - Challenging materials mix for Additive Manufacturing
- Source problem limitation
    - Representative domestic end user profile
        - To provide a manageable set of challenges to be processed
            - Provides a meaningful solution and prototyping/feedback opportunity

The restrictive elemental areas will serve as a vehicle to demonstrate the outcome of the methodologies. They will not be a major in-depth focus in their own right.

1.3 Methods

In addition to the thematic review of the literature, images and publications, research training has been undertaken and is ongoing in the appropriate software and hardware. This will provide a sound foundation for the furtherance of the research. This training includes autonomous practical skills for operating university equipment.

	Analyse Design Requirements/ conflicts	Design Concept Creation	Simulation	Evaluate	Optimise	Human Modelling usage simulation	Review and Revise	Manufacture
Tools	TRIZ/SPSS Factor Analysis	Solid and Generative Modelling	FMEA/ Generative Platform	Human Designer/ Generative Iterations/ LCA Analysis	Rhino/Grasshopper/Fusion 360/Solidworks	Siemens Jack	Jack/Fusion 360/ Rhino/ Grasshopper	ROBODK/ Cura Slicing/Robot KRC/ Robot Extruder Hardware & Software
Process	Eliminate conflicts/ Identify 'Critical to Quality' features.	Model initial concepts/ creation of complex geometries/ Parametric Customisation	Ensure the components and subassemblies operate together	FEA to assess performance in use and LCA to establish the impact of the product	Identify problems and optimise for the expected lifecycle	Identify ergonomic issues through cyclic use with a multiple end user profile	Modify in response to specific results of the Human interaction with the product	Manufacture in one process step, eliminating lead time and allowing Mass Customisation.
Design Outcome	Eliminate Design 'Trade-offs' leading to the establishment of unique solutions	Model Assemblies attaching attributes to them/ create BOM's and Drawings from the model	Identify structural, Operational and interaction problems, pre-production.	Identify pre-manufacturing quality and environmental issues, adjust and re-evaluate	Improve overall durability and strength, reduce wastage. Reduce in service failures	Correction of impending product/ human interface problems, increasing customer satisfaction	Crucial to furniture products is their ability to interface well with their human users	Fast creation of prototype components/ jigs/ multiple products on one machine/ SMED

Fig.1 Design, Simulation and Manufacturing Methods Framework (Fox.A, 2020)

The practical training & use of these software platforms has been greatly beneficial in further informing and enhancing the literature review process and helping to focus the research while identifying the extents to which opportunities possible through these mediums can be exploited by the Integrated Platform.

1.4 Contributions to knowledge

- Demonstrated the application of Generative Design and Shape Grammar to create sustainable, aesthetic, and easily mass customisable furniture products via Robot Based Additive Manufacturing (RBAM).
- Established the method to create previously uneconomic furniture structures in a sustainable manner using Robot Based Additive Manufacturing, creating thought-provoking aesthetic qualities and unique functionalities with the potential to leverage the added functional benefits of emerging smart materials technologies.
- Development of an integrated problem-solving strategy for the analysis and application of disruptive technologies for the future development of Sustainable Furniture Manufacturing.
- Creation of a physical Robot Based Additive Manufacturing Cell integrating the generative designs and robot-based additive manufacture with potential extension to a full-scale manufacturing platform, and demonstrating these integrated Design to Manufacturing technologies may also be instrumental in producing sustainable products which are far more appealing to an increasingly demanding and environmentally aware customer base.
- Demonstrated the potential of Environmental Product Impact Profiles of Generative Designs to inform and create Unique Selling Points (USP) to customers through assessment of the product Life Cycle Assessment (LCA).
- Reviewed and evaluated of these developments for extended and future research development.

2. Chapter 2 Literature Review

2.1 Environmental drivers and government initiatives

The main drivers for the development of Environmental Policy changes in manufacturing industry are as follows:

- Projected world population growth up to 9 billion by 2050 (UN,2011)
- 2.9 Planets worth of materials required by 2050 (WWF,2012)
- Increase in demand for water of 140% by 2030 (Mackinsey Global Institute,2011)
- Increase in demand for land of 250% by 2030 (Mackinsey Global Institute, 2011)
- Energy demand increases projected to increase by 80% with fossil fuels providing 85% of the mix (OECD, 2012)
- World GDP is predicted to quadruple by 2050 (UN, 2011)
- 4 billion middle income consumers in the world by 2030 (WBCSD,2008)

The results of the above mega forces are predicted to increase levels of Greenhouse Gas Emissions leading to a projected temperature rise of two degrees centigrade by 2040 (OECD, 2012)

These impacts will lead to basic resources being diverted to maintain the needs of the human population. Manufacturers from all industries will be forced to develop ultra-efficient processes and products. These changes will also create a requirement to manage far higher levels of Supply Chain disruption and risk.

Due to cost or capability factors most UK manufacturers have significant parts of their Supply Chain located overseas and 20% have more than half of their suppliers outside of the UK. Asia and the Pacific Countries supply materials crucial to the UK manufacturing Sector (Deloitte,2012)

Some UK manufacturers have already started to respond to these challenges by sourcing from multiple suppliers, using home & local suppliers despite effects on quality and costs. (EFF, 2012a) However many SME companies typical of the Furniture Industry do not have any contingency plans to manage these disruptions (UNISDR, 2013)

Demand for metals will increase by 30% – 50% by 2020 and much higher for Steel and Copper (Chatham House, 2012)

Peak oil scenario is estimated to occur by 2030 (Sorrell et al., 2010) Trends in the demand for land show an increase in competition for land used for Bio-energy production, crops and livestock, with forest and other land decreasing. (Smith et al.,2010)

Raw Timber and the guarantee of its origins 'Chain of Custody' are currently under the control of such schemes as the Forest Stewardship Council (FSC). These are effective to a point but in practice are open to massive abuse and the development of methods to guarantee supply chains can be assured are still being developed. The abuse of the stewardship, especially in the case of Exotic hardwoods, is leading to the large-scale elimination of virgin rain forest by unscrupulous suppliers. The Chain of custody for other materials are causing even more problems for manufacturers. This is due to multi-tiered suppliers and manufacturers of the products, who may be reluctant to release information because they have intellectual property rights. This is not encountered with Raw Timber.

In some other industries and services the idea of Block Chain, audit trails are being considered. This is a technique which has been largely applied to financial transactions e.g., Bitcoin transactions etc. The block chain system maintains an electronic record of all transactions throughout the lifetime of the materials. Because the records are held on numerous databases it is incredibly hard for the records to be changed or falsified.

National governments are beginning to recognise that there is a need for Infrastructure and Government support providing momentum towards a contraction in Globalisation and the strengthening of nationalism, e.g., Brexit, US retreat from global co-operation etc.

This has highlighted the need to develop more vertically integrated Factories dealing with Raw Material processing and the integration of logistics in with manufacturing processes.

Government interventions and initiatives have included the following:

- **USA – Smart Manufacturing Innovation Institute (SMII)**
  - Pacific northwest, California, Texas, North Carolina & Rensselaer Polytechnique
    - To research and encourage implementation of innovative manufacturing and materials technologies
- **Germany – Industrie 4.0**
  - 200 million Euro investment in academia and business to encourage the development and implementation of digital processes and technologies.

    - Establishment of a balance between data privacy and data sharing to create new products.
- **China – Made in China 2025**
    - A network of manufacturing technology centers set up by the Ministry of Industry and Information technology (MIIT)
    - It is more than just Digital Technologies, aiming to improve overall quality and efficiencies of manufacturing.
        - More than manufacturing, also looking to enlarge digital technologies to incorporate Sales, Marketing, Engineering, Design & End Users.
        - This is a response to the growing Chinese middle class, rising wages and new competition from new low-cost economies.

It is recognised that the technological developments in Artificial Intelligence (AI) & the Industrial Internet Of Things (IIOT) are so fast moving compared to previous 'Step changes' that companies who are not looking seriously at implementing these advances may not be able to compete within a decade. This has been seen in examples such as Kodak and Polaroid where the digital advances first made film redundant and then cameras were superseded with phones.

Government intervention is to create a support framework not only for manufacturing but for data driven manufacturing. This form of manufacturing is not new, it is nearly a century old and has been developed from the pioneering works such as:

- Frederick Winslow Taylor – Scientific Management
- W Edwards Deming – Statistical Process Control (SPC)
- Six Sigma etc.

The major difference is that data driven production, analysis and manufacturing operations, are now largely required to be 'Real Time.' The technologies are all encompassing areas such as:

- Predictive Maintenance
    - Projected 10 – 30 % saving in maintenance costs
- Automatic Data Capture
- Cloud Based data analytics – 'Big Data'

The goal being Autonomous Production and Prosumption with the systems controlling:

- More efficient configurations

- Adjusting to real time fluctuations in demand
- Production planning and scheduling

Fast moving developments have also created challenges for Governments in other concomitant areas. Foremost amongst these is providing Manufacturing Industry with the skills it requires to make implementation possible.

Manufacturing Industry as a whole has recorded a 10% increase in overtime to fill the Gap in Skills. There is a significant change taking place from low skilled and dangerous jobs to technician and programming jobs. Governments are using apprenticeship initiatives coupled with University Advanced Manufacturing Programs and vocational college two year short courses to fast track development and Life Long Learning for Manufacturing.

Environmental support and legislation is also key in the developing mix.

Critical issues which must be addressed by governments and authorities include:

- How will society alleviate current and future damage?
- How will society adapt to a changing world?
- The way we do things will have to be re-conceptualised.
- Developing co-operation between scientists, engineers, social scientists and consumers.

The UK has competencies leading some sectors, overall, however as a nation only ranks around the middle of the EU-27 Eco-innovation index.

Initiatives are available to industrial producers, an example of which is:

- Renewable Heat Incentive (RHI)
    - Using waste materials from the manufacturing process for the generation of heat and electricity. This system results in a financial benefit for the organisation dependent on the quantity of heat and power produced.
- Waste Electrical and Electronic Equipment Directive (WEEE)
- Evaluation and Authorisation of Chemicals (REACH) Decoupling Environmental Impact from Industrial Growth (Japan & China)
- 3R's Reduce – Reuse- Recycle
    - Sound Material Society- regulation of targets for resource productivity
    - Top Runner – best product in class becomes the new legal standard.
    - Closed loop business models - cradle to cradle - circular economy.
- Revise Design Education in Furniture product technologies to refocus on:

  - Products designed for durability, standardisation of components, modularity…ease of disassembly (Allwood and Cullen, 2012)
  - 'Industrial Ecology Initiatives' to establish waste from one process as raw material for another.

There is also a significant play off between financial and environmental considerations.

- Traditional focus was on financial costs with health, environmental and social impacts appearing as lower priorities. The paradox is that the obsession with financial cost to the exclusion of these other fields usually means that they become a financial cost in time. This cost is often paid for by someone else.
  For Example:
  - Oil – wars in distant lands
  - Health – NHS: Chemical emissions inducing cancer and heart disease.
- The next generation will also pay to clean up the pollution left behind. In effect we are borrowing money from them to pay for over consumption and high levels of pollution & waste.

There are two quotations which put a spotlight on the immense importance of changing our manufacturing and consumption attitudes and the development of Sustainable alternatives:

> "We're finally going to get the bill for the Industrial Age. If the projections are right, it will be a big one: The ecological collapse of the Planet."
>
> Jeremy Rifkin (World Press Review, 1989)

> "We shall require a substantially new manner of thinking if mankind is to survive."
>
> Albert Einstein

Consumer attitudes to alternative approaches to consumption is a fundamental element. Sustainable production and consumption require major changes in Core Business Processes. These were traditionally based on linear production processes and a throwaway mentality.

Alternatives may incorporate the idea of circular flow of products and materials, in both the production, consumption and re-use phases.

- Extending the life of Products (buying second hand, Upcycled Products)
- Access based consumption (leasing or renting)
- Collaborative consumption (sharing)

Data concerning consumer attitudes towards these changes is scarce particularly in furniture and home products.

The overall trends in Furniture consumption show that consumers' attitudes vary significantly:

- Buying second hand & short-term rental – largely positive
- Long term renting – largely negative
- Collaborative consumption – higher acceptance for rarely used products (Edbring et al., 2015)

Products with the highest environmental impact are particularly suitable for re-use. Traditional furniture is an example of a product with the highest environmental impact in the extraction phase i.e., logging which makes it especially suitable for re-use (Berlin, 2012)

Selling product use or functions promotes manufacturers to produce durable products to maximise profit on the units of service or function they deliver.

Attitudes towards buying second hand or reconditioned products are shown in a number of studies where the main drivers for this are practical and economic (Clausen et al.,2010) Joung & Park found no link between environmental attitudes of young consumers and second hand/reconditioned buying behavior (Joung & Park-Poaps, 2013)

An interesting motivator for buying second hand/reconditioned goods was – the preference for high quality used products over new low-quality products (Clausen et al.,2010), while Guiot and Roux (2010) identified that some buyers are driven by a desire to distance themselves from a wasteful commoditised lifestyle and see the benefits of consuming less. They also felt that this form of buying expressed their personalities more, especially when they went further and customised these products themselves (Guiot and Roux, 2010).

Fig. 2 ‘Designer’ Upcycled furniture products. (Shutterstock)

Literature search indicates that there are few research studies exploring consumer attitudes to buying second hand/reconditioned furniture, renting, leasing or sharing furniture and home products.

Directions for the future will need to re-invented to achieve a robust 'green revolution' to feed all the needs of the growing population, satisfaction of increasing demand and allowing us to thrive within the means of the planet.

- Circular Economy (CE) requires significant manufacturing focus at the design stage.
- The World Economy is currently only just over 9% 'circular'. This figure demonstrates the immense potential for beneficial review.
- The '4th Industrial Revolution' and the increase in digital technologies is providing great momentum and potential for innovation & transformation.

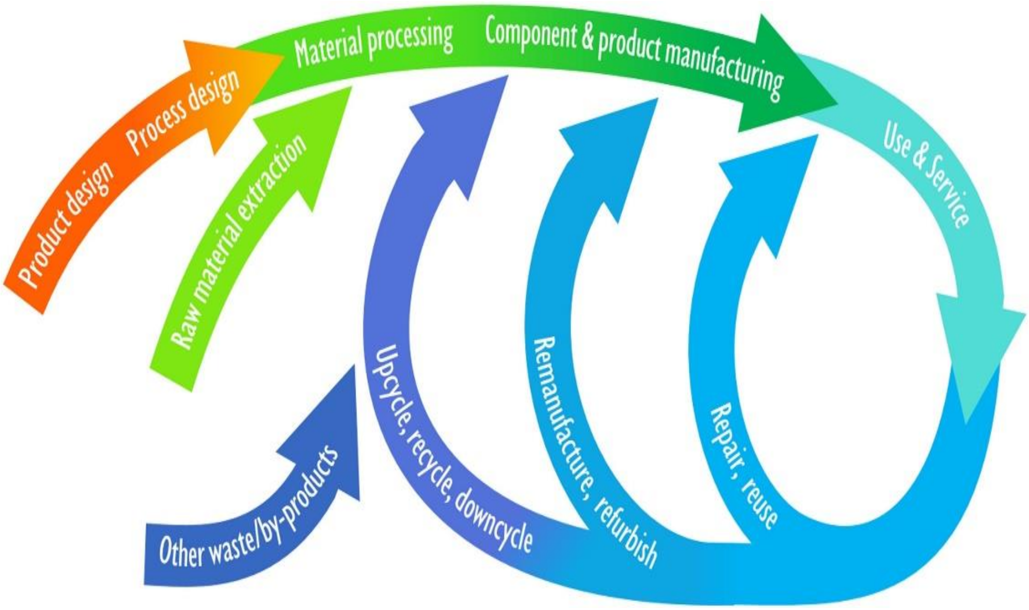


Fig. 3 Circular Economy (Despeisse and Ford, 2015)

- Development and implementation of 100 % water based UV cured glues, stains and top coats to timber products, thus reducing VOC emissions
    - Potential costs over solvent based finishes
        - Longer curing time
        - Increased energy costs / utilisation
        - Increased handling damage (extended curing period)
- Reduce Greenhouse Gas emissions.
- Reduce water consumption.
- Reduce energy consumption
- Development of Chemical Custody

  - Materials chemistry assessment – red to green categorisation

The following predictions demonstrate the potential of successful implementation of Circular Economy Strategies

- India could reduce emissions by over 40% while taking no additional action (Ellen MacArthur Foundation, 2018)
- Europe could reduce emissions by 8.2 % and increase employment by 2.9 % by investing 13% of labour taxes in resource use and disposal initiatives.
  (Ex-Tax & Cambridge Economics, 2018)
- If 5 EU member states maximised renewable energy and energy efficiency alone, they could potentially reduce Greenhouse Gas Emissions by 50%. If Circular Economy strategies were added this figure would potentially rise to 70% (Club of Rome, 2017).

Comparatively the overall environmental impact of the Furniture Industry is low, however the themes and goals of the 'green revolution' are universal in nature.

Goal 1: Minimisation of Virgin Material extraction from the lithosphere & biomass production. Extraction should be re-generative.

Goal 2: Scattering and loss of materials should be minimised with the design of technical materials enabling high recovery rates without losing quality and functionality.

Strategy: Use and re-use of existing stock materials. Ensuring that those resources already produced are fully exploited.

In order to stimulate materials cycling it is essential to create incentives & cost effective frameworks for re-processing of these reserves.

There is a breakeven point at which Additive Manufacturing becomes attractive based upon the notion of Mass Customisation and the number of units and variants produced.

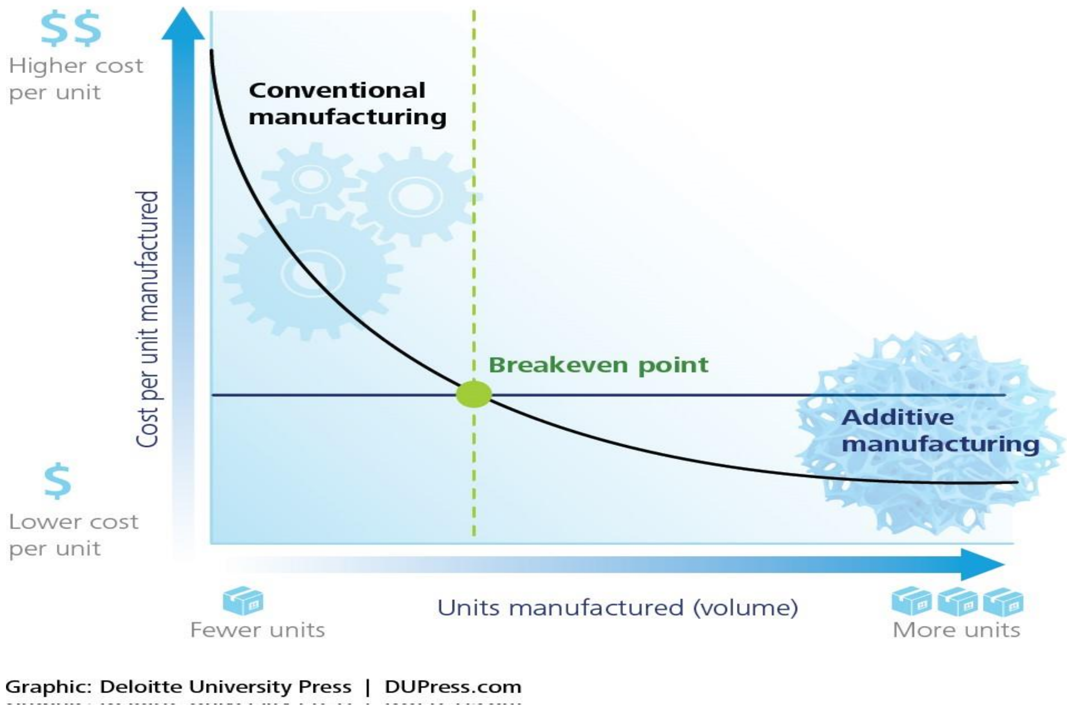


Fig. 4 Cost per unit Conventional Vs. Additive Manufacturing

2.2 Traditional vs Additive Manufacturing

Additive Manufacturing (AM) technologies are currently utilised for single or short run production but can be extended to produce larger volumes without any significant rise in direct manufacturing cost.

AM increasingly makes sense in volume production, as end users can choose endless combinations of colors, shapes & sizes without a resultant increase in lead time. This gives rise to the very real opportunity to achieve 'Mass Customisation'. Given this scenario it leads to very relatively little rise in manufacturing costs, even as volume demand grows.

It can be used to produce a range of different products with the elimination of traditional setup times and the significant reduction in levels of waste. It represents an extreme application of 'Leagile' Manufacturing and illustrates the very real opportunities for future Mass Customisation in the Furniture Manufacturing Industry. The design possibilities using Additive Manufacturing technologies are immense and many produced from a single machine operation with minimal setup between products.

Fig. 5 Voxel Chair, Bartlett School of Architecture, UCL

Fig. 6 Liquid Glacial Table, Zaha Hadid

A key issue would be the end user perception of products manufactured using polymers and composites compared to traditional materials combined with the aesthetics, look, feel and design complexity of such products.

While many are trying to prove that furniture can be printed it is equally important to try and print furniture that people actually want.

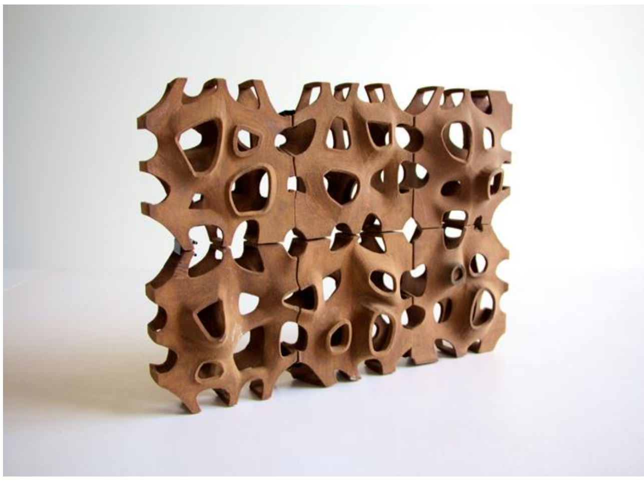


Fig. 7 ‘Poroso’, simulated wood modular printing, (Emerging objects)

In a recent conservation project at Kew Gardens where the Pagoda is being restored, the long-lost dragons are being put back onto the structure after nearly 200 years. Due to several factors many dragon figures are being manufactured using Additive Manufacturing techniques, with only the bottom 8 dragons (out of a total of 40) being hand carved using traditional methods. One major factor was indeed the weight of the finished items which were to be placed on a structure that was not specifically designed for such weight. The Dragons produced by AM are hollow and finish at around 8Kg. Despite this factor the production of these items using AM has sparked a great deal of controversy amongst traditionalists decrying the demise of traditional craft skills.

Fig. 8 Images from 3D Systems Manufacturing Site visit, High Wycombe Bucks January 2018

Conservation and recreation of ancient artefacts is seen below in Beijing China.

Fig. 9 Silk Road exhibition in Beijing. It featured 3-D printed replicas of Buddha statues from the Mogao Grottoes in Dunhuang, Gansu province. Photo via Xinhua.

Additive Manufacturing is not a new technology it was established some 30 years ago. It has been mainly employed in technically advanced applications in the Car Industry, Aerospace and Medical to produce Prototype parts, molds and recently finished functional parts. This was due to the high cost of the processing equipment, complexity of the parts and the technical nature of the products.

Since the end of the last major patents with Stratsys and 3D Systems for FDM in 2009 and subsequent reduction in equipment costs the technology is now starting to be used in a wide range of new applications which were previously not commercially viable. The speed and scale of the Additive Manufacturing is also developing very quickly, making the options and scope for production much greater. The industry is still in its infancy and many technical advances and new applications are still emerging. It may take a number of years before AM truly revolutionises manufacturing.

AM may well initiate the 3rd Industrial Revolution that will have significant organisational, economic and social consequences. Evolving dramatically in a generation, much faster than the previous two manufacturing revolutions.

E.g., The US hearing aid industry changed 100% to additive manufacturing in less than 500 days. Not one company that remained with its traditional manufacturing methods survived.

Jeremy Rifkin, 2012 believes that AM will be a significant technology in the 4th Industrial Revolution.

Examples in parallel industries can be seen emerging, for example, Karl Lagerfeld of Chanel showed 3d Printed dresses based on traditional designs at Paris fashion week in 2015 and stated that 3D printing was the way that the future was going to unfold. Danit Peleg produced a whole clothing range via 3D printing a short time after learning the technology for the first time. The use of these materials and techniques may well initiate a revolution in design and consumer demand for these products.

AM has four major benefits over TM

- Cost
- Speed
- Innovation
- Impact

It will not immediately take over from TM methods but will initially dominate specific areas to which it is particularly suited. Once these areas are established and the potential is recognised and developed, it is expected to grow exponentially. This exponential growth will have far reaching effects on traditional manufacturing. It may give rise to micro-manufacturing which will be decentralised. These micro manufacturing operations will be close to the customer base and will eliminate the need for the transportation of finished goods for long distances, reducing one of the main contributors to environmental impact. Wholesale operations may also be greatly diminished. Preparations for this can already be seen in joint ventures, for example, the setup of 3D printing factories by SAP/UPS around the world to prepare for the changing landscape of manufacturing.

Fig. 10 UPS/SAP Fast Radius printing facilities

On demand manufacturing in the locality of the customer will reduce the need for inventory. The ability to make modifications and redesigns without a significant cost penalty makes AM extremely flexible both for the manufacturer and end user. In TM it is estimated that 60% of all designs submitted for tooling are subsequently redesigned while in production leading to increased costs and delays.

AM is a powerful tool to improve manufacturing efficiency, streamlining traditional methods and reducing many environmental issues associated with traditional Mass Production. It also has the potential to reduce supply chain complexity.

AM can be used initially in conjunction with existing design and traditional manufacturing processes e.g., Short run silicon molds which allow new products and components to be produced, tested and modified at minimum cost and delay. Such molds can generally produce from 200 – 500 units before they need to be replaced or upgrading to production tooling.

It can be applied & tested by first using it to create jigs and fixtures for traditional manufacturing. Once the confidence levels and knowledge grow other opportunities will become apparent to organisations for application directly to product manufacturing.

It encourages the growth of individuality and creativity in the design of many product types and may cause major disruption to established labor practices and markets. Some predictions indicate that in the medium term over 80% of traditional manufacturing jobs will no longer exist in their current form.

AM in conjunction with digital design approaches can enable production of entire products in one cycle minimising the amount of assembly and post processing needed. The number of components and sub-assemblies can be greatly reduced in larger products compared with TM methods.

TM – machinery operates in series producing similar products quickly with high tooling & fixture costs to be amortised over large production volumes.

AM – is a parallel process combining operations and making mixed families of products, concurrently, at a relatively slower speed. Setups consist of 'warm up' and 'cool down' times and are a small issue for economies of scale. The equipment is multi-purpose so can be scheduled more flexibly between varying products to meet fluctuations more effectively in demand profile.

Skills profile requirements for the AM technologies has also changed. Equipment training can now be applied to wide product families, where traditionally training was very product centered and related to very specialised and product specific processes.

The projected worldwide revenues for AM are predicted to rise dramatically.

2013	$3.07 billion		
		62.8 % increase	
2016	$5.00 billion		
		241.6 % increase	684% in 7 years
2018	$12.08 billion		
		173.8 % increase (Projected)	
2020	$21.00 billion (Projected)		

(Wohlers, 2014)

McKinsey reported that '3D Printing' was "ready to emerge from its niche status and become a viable alternative to conventional manufacturing processes in an increasing number of applications. In 2014 3D printing technology sales accounted for one third of the industrial automation & robotic sales in the US, this is projected to reach 42% by 2020 (McKinsey & Co., 2014).

Digital operational support structures are essential to enable the integration of activities between designers, makers and logistics needs to be established. An open platform to allow design sharing and fast secure downloading of the design information will be necessary. This will then inevitably give rise to the need for autonomous control of printer operations, subsequent quality monitoring and the control of capacity issues, plus other functions required to support the manufacturing operation. The first companies to develop these platforms will benefit greatly by establishing the standards by which the new industry operates globally.

GE have now 11 patents and are working on developing the Industrial Internet. IBM with 19 patents is exploring and developing a system called “Software Defined Supply Chain”.

Cloud based artificial Intelligence developments may boost AM’s ability to add or change products instantly without the need for re-tooling and make real time changes in product strategy, such as product mix and design decisions.

There are many variants and choices when it comes to 3D data handling and file transfer, AM processes currently utilise more than 30 different file types.

These include but are not limited to:

- STL – Standard Tessellation Language (3D Systems)
- VRLM – Virtual Reality Modelling Language (.wrz) (Superseded by X3D)
- PLY – Polygon File Format
- WRL – Plain ASCII text file specifying 3D details
- OBJ – 3D geometry definition file format
- FBX – (Filmbox) Digital content creation file format (Autodesk)
- STEP – Standard for the exchange of product model data
- IGES – Initial Graphics Exchange Specification (Superseded by STEP)

All these file formats have their strengths and weaknesses. But there is no one single option that is an optimum solution for state of the art AM production. The most popular and widely used format is STL, but this format still has a number of practical problems, including the following:

- Objects don’t always print exactly how they appear on the screen renderings.
- There is no option for transferring data and printing objects with multiple colours, textures and materials.
- Surfaces may contain ‘holes’ if the density of the mesh is not appropriate to the model.

- In some cases file outputs may be very large and cannot be handled by the hardware.

With AM moving towards production of products as opposed to creating prototypes, a file format is required that clearly communicates the properties of the model to the equipment consistently without the need for direct human intervention.

Emerging Developments in this area can be witnessed in initiatives such as the 3MF Consortium. This is a developmental activity sponsored and supported by many the major companies involved in the area of AM. These include but are not limited to:

- Microsoft,
- GE
- HP
- SLM
- Materialise
- 3D Systems
- Siemens
- Stratsys
- PTL
- Autodesk
- Dassault Systems
- Netfabb

The 3D Manufacturing Format (3MF) aims to integrate all the key functions necessary to create fully dependable 3D models for execution by many different platforms, applications and hardware solutions. Its aim is to minimise conflicts with other 3D file formats. Its major deliverables are:

- Comprehensive – model, property and material information in a single database.
- Human Interface – Easy to read and develop
- Straightforward – Short, clear & fast verification
- Explicit – File data is always consistent from digital to physical
- Free – No Royalties, patents & licensing

The development of this format stands to greatly increase the efficiency and autonomy of creating and manufacturing 3D objects through AM.

2.3 Generative Product Design for the future of Manufacturing

Step change technology developments are often accompanied by intense social and organisational disruption. They are therefore usually accompanied by potent resistance from the established communities. Adjusting the organisations to reap the benefits of such changes often involves agonising re-invention of established practices and processes.

The unprecedented speed of Digital Product Design change will require paradigm shifts as opposed to a gradual evolution. Design practices will have to be radically amended to accommodate and exploit the potential of Generative approaches. The concurrent development of Additive Manufacturing has further speeded the adoption of Generative Design by enabling designers to realise digital concepts as real-world products.

In the context of Industry 4.0 there is clear agreement that the future of design and manufacture will be very different from anything we have known historically. Mass manufacturing, production lines and centralised volume manufacturing are all under momentous threat. However established operations have still been slow to respond (Gore,2013). This is attributed to the difficulty that leaders have in visualising what is so different, especially as the pace of change is so fast and relentless. This is so important as product design is so central to Industry 4.0 and as such it is necessary to create a new world view for digital designers through investment in research informing new strategies. (Cameron. N., 2017)

Comparable situations were experienced historically when early entrepreneurs faced converting their workforce from individual craftsmen to standardised component fabricators. This required the product being broken down into easily repetitive components (Forty. A., 1986) Many current design courses are still teaching traditional product design driven by volume manufacturing requirements with a view towards decreasing tooling costs and boosting output to realise slim margins and centralised manufacturing. This needs to change quickly to furnish industry with a new breed of digital designer (Nagy H., 2016).

Generative Design in the future will be established through the consideration of three key discussions:

- Relationship between Manufacturing and Waste in a circular economy, using bio-materials in bio-based processes to satisfy manufacturers and consumers personal environmental responsibilities.
- The effect on society of centralised manufacturing and the future risks inherent in this economic strategy eg. Detroit essentially going bankrupt in 2013 due to the demise of its mass manufacturing (Bomey N., 2016).
- The impacts of imminent fast moving digital technologies undreamed-of even at the start of the 21st century.

Whilst there is evidence of research publication into designing with additive manufacturing there is very little research embracing the imminent paradigm shift to manufacturing through this digital revolution (Liu, et al, 2019) Many educational programs do not go much further than practical CNC machining and laser applications etc. although digital scanning is starting to gain some momentum now in conjunction with solid modelling.

Barros.M et.Al. and Weihua. Z do research elements of Generative Design specifically for Furniture Products, but this research is limited to elements of early generation Shape Grammar approaches to generative design for conventional furniture products. There is no focus on linking these techniques to novel manufacturing methods or the assessment of Environmental Impact of the resultant designs.

Tomorrows' lifestyle and patterns are virtually here, they are right on our threshold and transforming our experiences all be it that many are not physically present but exist as electronic data governed by guidelines and structures in the digital environment. This has the potential to move Product Design from co-creation to a prosumptive model to design and manufacture products ourselves. In effect it is a return to a cottage industry model not seen since the Industrial Revolution. This is an understandably distasteful to designers in relinquishing control of proportion, scale and detail to determine the ergonomics and the aesthetic form of a product.

Shortly technological developments, enhanced information and computing infrastructures will bring new ways of for enterprises and individuals to create, learn, produce, innovate and collaborate in a smart, data driven networked learning environment.

Form is a key issue in the design of Furniture. Generative design affords the designer the ability to consider truly unique options which were in essence beyond the scope of a human design team. This form of design is in itself endless achieving a balance between the practical and the transcendent. One very important realisation is that despite the role of the Designer being fundamentally changed generative design significantly retains expression and artistic creation through truly unique product outcomes. The potential value of the generative approach to the designer is its ability to create multiple iterations of the design with the additional option of the client being able to ‘Prosumptively’ engage with the design parameters creating a truly customised products for themselves.

One major constraint at the moment is the ability of the 3D printing process to create objects of larger proportions, hence prompting research such as this which will examine the options for creating those products and the interactive manufacturing technology options to do so. (Davies, S., 2018)

In order for this genre of design to succeed in the future Education and Research activities need to embrace these digital developments wholeheartedly, realising that a whole new ontology needs to be established. Educational agility is needed more than ever to ensure its relevance in the rapidly changing digital environment in order to translate their work into successful industrial manufacturing practices. Its definition, allegiance and boundaries will need to be interrogated through academic research.

Dean (2016) argues that:

“At stake is not the loss of distinction between areas of expertise, but rather re-imagine the terms on which distinctions are made. In short the situation presents the opportunity for recalibrated conceptions of design where the expansion of design can only be accounted for through re-conceptualisation of its boundaries.”

A parallel to the exponential potential of the emergence of Generative Design and Robot Based Additive Manufacturing can be seen in the example put forward by Gore (2013):

“Consider the increased flow of information throughout the world following the introduction of the Internet and the World Wide Web. Elements of the old information pattern began to break down. Many newspapers went bankrupt, readership sharply declined in most others, Bookstores consolidated and closed. Many business models became obsolete. But the new emergent pattern led to the self-organisation of new business models and volumes of online communication dwarfing those that characterised the world of the printing press.”

Generative Design and Robot Based applications for Additive Manufacturing coupled with the fast-paced development of cloud computing technologies can be the basis for a revolution in worldwide distributed manufacturing systems, forming the basis for new business models in which digital product designers can flourish, thus creating the step changes for the implementation of true Industry 4.0 practices (Greenfield, 2002)

A key element of this research identifies that the Megatrends and Drivers identified will create a profound trajectory of social, economic, environmental, and technological change occurring over the coming decades. This change will initially be gradual, with some resistance from traditionalists, but as time progresses the expression of these changes will inflict 'explosive' impacts not only on manufacturing but also education and research expectations. Lifelong learning will be a necessity to keep up with this fast-paced future.

The continued rise in computing power combined with ever greater social, economic and environmental issues in a virtual world will force the as yet limited uptake of mass customisation and the development of better additive manufacturing materials & processes to improve structural properties and surface finish while eliminating the need for post processing.

As with Furniture manufacturing no sectors will be able to avoid the developments in this discipline, eventually creating more overt connections and collaborations between computer-based disciplines in engineering and design with the values, understanding and skills from other practices, opening lines of communication to areas such as fashion, architecture, medical applications etc. to create a new and vibrant platform for future collaborations and developments.

2.4 Robot Based Additive Manufacturing.

The implementation and adaption of robot-based manufacturing harks back to the traditional practice of applying Concurrent Engineering (CE) considerations in terms of the developments in technologies and computing power. Designs were often too difficult or uneconomic to produce but are now viable thanks to various forms of Additive Manufacturing. These developments put the focus firmly on changing the manufacturing disciplines to those which can deliver these new ground-breaking & aesthetic designs in the most effective way. The many considerations and parameters applied during the Generative Design Process pave the way for results offering reduced environmental impacts, enhanced product life cycles and subsequent re-use or recycling.

There are drawbacks with Additive Manufacturing, one foremost among these is the ability to create larger products. Robot Based Additive Manufacturing overcomes some of these constraints using External Axes and Rail Systems etc. These additional functionalities afford Robot manufacturing unique flexibility.

With enhanced cloud computing capabilities the Robot Development environments are far more capable of dealing with complex geometries and product forms. Much of the cell functionality can be developed in the virtual environment of the online robotic cell Graphical User Interface (GUI).

Robot manufacturing has been used to some degree already in the Furniture Industry mainly in the areas of welding, spraying and packing. The difficulties arose when the robots were expected to have additional senses in operations like the sanding of solid wood etc. The ability of robots to also monitor and assess operating pressure and normalisation to complex surfaces while sanding etc was a problem as this could lead to damage and inconsistency. These problems have now been largely overcome with the use of pressure monitoring sensors.

Robot Based Additive Manufacturing although not used to any degree in today's furniture Manufacturing Industry, it has the potential to be a significant disruptive technology when combined with Generative Design. The issues of surface finish can also be resolved by the development of hybrid robotic processes. For example, interchangeable Additive Manufacturing (AM) and Subtractive Manufacturing (SM) tool heads. With current Robot Development environments (e.g., RoboDK) these head variants can be easily modelled for efficient collision protection and functionality (Fusaomi, et al., 2006).

There are few current research studies examining the potential scope for full scale Furniture Manufacturing using Robot Based Additive Manufacturing, although there are notable creative furniture making artisans who are adopting these technologies for the manufacturing of their ground-breaking Furniture Designs. This indicates the embryonic acknowledgement and realisation of the potential benefits of these technologies.

There is huge importance in the need for the UK Furniture Industry to embrace these new technologies for their future success and mitigation of Environmental Impacts. In 2019 McKinsey and Company produced the report: "The Next Horizon for Industrial Manufacturing: Adopting Digital Technologies in Making and Delivering" which highlighted the significance of the impact of Disruptive Technologies on Industrial Manufacturing in general. The specific 'disrupters' identified in this report were Additive Manufacturing and Robotics, with their intersection presenting unique potential for robotics companies and their clients.

With these processes no longer hampered by the constraints of conventional manufacturing technologies, they have brought about positive potential disruption in transforming furniture design and manufacturing practices.

Additive Manufacturing is based on the need for accurate steady repetitive motions to build layered products, to which robotics is an ideal solution having these plus excellent repeatability and control.

2.5 Life Cycle Analysis

This element of the contribution is to complete and verify the circle. Generative Design technologies to produce overtly original design solutions beyond the capacity of even the most capable Human Design Teams, subsequently manufactured using Robot Based Additive Manufacturing technologies, potentially reducing the logistical elements of materials supply and product delivery. The manufacturing process is flattened by the ability to produce the most complex geometry in one cycle and as one main assembly, thus eliminating manufacturing time, capital equipment resources and traditional manufacturing wastes.

However, from my experience there is a need to develop a consistent strategy, employed by the manufacturers, to quantify and confirm the benefits of these approaches. This measurement can not only be used to identify economies and savings to the manufacturer but also be employed to communicate the environmental impact of such advancements to a far more astute and aware customer base, hence increasing sales and enhancing the environmental profile of the company.

The traditional concept of never-ending continual growth in GDP and other measures of productivity are potentially flawed and a re-focusing may be required to give far more weight to the concept of customisable and bespoke products manufactured locally, with longer life and better suitability for recycling and re-use as the major product characteristics. An EU based study carried out in 2010 suggested that one third of consumers would be willing to pay 10% premium over the standard price for Furniture Products with sound environmental credentials. (Federlegno, 2010)

Hence the sound evaluation of this industrial sector in improving the environmental and the global sustainability of the supply chain is of premium significance. Life Cycle Analysis although not widely used currently is one of the most reliable methodologies for substantiating and scrutinising the environmental impacts during the life cycle of a furniture product and as such should be an important element in any decision making in the development of environmentally friendly products (Baumman and Tilman, 2004). It should however be noted that traditionally and currently that despite the significant capabilities of LCA, the databases employed are still very underdeveloped and require considerable interpretation in their application.

LCA has the potential to eliminate many environmental impacts that are a result of poor design decisions. The product design phase is on average responsible for 70% of the final cost and environmental impacts. The environmental decisions made at this stage are critical as they follow the product through its entire life cycle. The Furniture industry is a key emitter of Volatile Organic Compounds (VOC), Formaldehyde and other noxious substances currently, strategies to change process and methods is paramount in the fight against climate impact (Gonzalez-Garcia, et al., 2011).

The disruptive technologies and methods discussed, combined into a platform for the future development of the UK Furniture Industry, provides a strong foundation on which to base future research and development using the TRIZ decision making model to develop ground-breaking aesthetic product and material combinations being manufactured in an environmentally positive manner.

2.6 Consideration of Current Materials

The other key area of development is around materials science and although this does not feature heavily in this research it should be recognized as a complimentary and developmental issue which will have a great potential to enhance the Life Cycle Environmental impact of products, especially those that are additively manufactured.

The common materials used currently in the Additive Manufacturing sector are:

- Polylactide (PLA) – low cost, biodegradable thermoplastic, made from corn/sugarcane.

- Acrylonitrile Butadiene Styrene (ABS) – more brittle, higher melting point, better mechanical properties than PLA. ABS is also suitable for post processing and finishing.
- Specialist Polymers developed for specific end uses.
- Polymer Composites- shown to have increased mechanical properties and mimic other traditional materials.

Fig. 11 Gemini Chair, 44 combined composites, Designer and Prof. Neri Oxman, MIT

In addition to the polymers, a range of other materials can be used in the process:

- Resins
- Rubbers
- Ceramics
- Glass
- Concrete
- Metals (Bogue, 2013)

Depending on the AM process being used it drives the development & investigation of new polymers & composites be they liquids, powders or filament composites.

There is now a strong desire to develop the use of sustainable wood waste, natural materials and bio polymers to extend the eco-credentials of AM, e.g. a team at University of Berkley 'Emerging Objects' are exploring the use of recycled used car tyres of which there is currently a massive 260 million available for processing.

Fig. 12 Materials transition and development, Car Tyres, University of Berkley, USA.

2.6.1 Overview

It is recognised that an increasing problem with waste & pollutants, especially environmental concerns regarding petrochemical based polymers. These developments are significant to the field of Additive Manufacturing and is a key context within which this research is set.

Over 8,000,000 tons of polymer based materials are entering the Marine Environment every year, of which currently only just over 9% is recycled. This is cause for great concern as this material takes in some cases up to 450 years to fully degrade forming a 'soup' of plastic micro particles. The cumulative effect of this pollution, unchecked, is that by 2050 the volume of plastics in the ocean will be equivalent to the volume of fish. This then has the potential to enter the food chain e.g., European shellfish are predicted to consume in the region of 6,400 micro-plastic particles per year.

For further research information on materials development See APPENDIX A.

2.7 Summary Discussion and Knowledge Gap

The environmental drivers Identified are very compelling and force one to consider the very great need for changes in existing design to manufacturing practices and thinking. These issues combined with the necessity for speed in terms of adopting and keeping abreast of fast-moving technologies and reducing 'harms' in an expedient manner, require traditional industries such as Furniture Manufacturing to adopt a new way of thinking.

As clients become more informed regarding environmental impact there is also a need for our products and demands on the biosphere to adapt to this new world.

A re-conceptualisation is becoming more necessary. Part of this is to move away from the traditional focus on immediate process costs, while taking a longer and broader view of those future hidden environmental costs which will impact the next generation. This may take many forms including the customization and functionality of designed products, considering length of life, extended second life and end of life recycling. Therefore, to achieve these aims manufacturing industry needs to focus on these issues at the initial design stage, producing novel forms, structures & processes. Digital technologies now furnish us with great potential & momentum for change, despite traditionalists decrying these approaches.

High levels of growth are already being witnessed in some manufacturing sectors which now needs to be translated and adapted to Furniture Manufacturing. Our future lifestyles and aspirations can be realized through the creative application of these disruptive technologies. These technological applications combine to form the potential for a new creative learning environment which is real time and data driven.

These technologies combined with significant advances in materials technologies give us the opportunity to add a fourth dimension to our products, adaption of the product in response to stimuli over time.

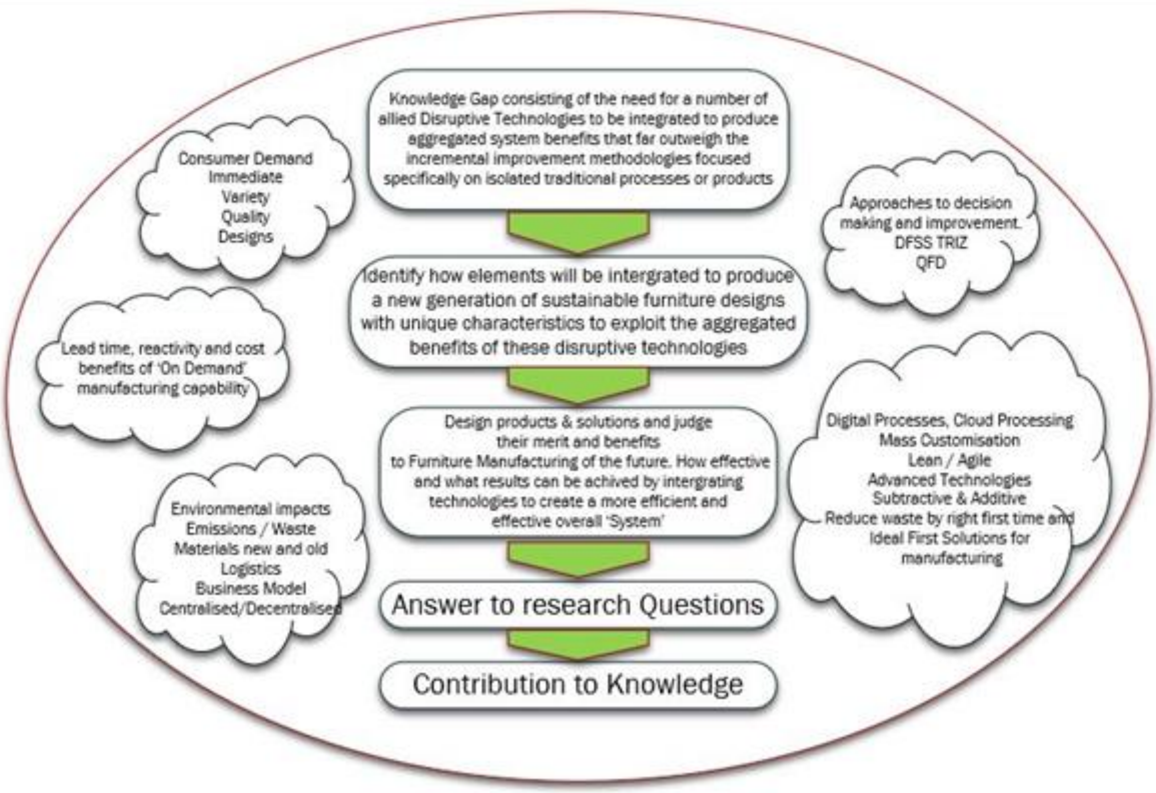


Fig: 13 The bigger Picture: Model based on Steppingstones to achieving your doctorate

(Vernon.S, McGraw Hill, 2012)

The challenges are multi–faceted and systematic. The development of End-to-End manufacturing in the Furniture Sector is problematic as it has a wide range of products and finishes, very short production life cycles together with limited and low skilled resources and IT systems. The Furniture industry is one of the most fragmented manufacturing sectors in Europe with over 70% of companies being SMEs. Their information systems are not consistent causing problems when trying to share data with other ventures and many companies still design 'by hand' or use very specific software impeding the use of digital exchange and control.
(European Furniture Industries Confederation, 2012; Centre for European Policy Studies, 2014)

The Knowledge Gap relating to the Furniture Industry revolves around its reluctance to move away from traditional methods. There is a requirement for a Strategic Integrated

Sustainable Design to Manufacturing platform to demonstrate the potential for the exploitation of fast-moving Disruptive Technologies. This platform is multifaceted and based upon the initial research would include several essential elements to create a fully circular system.

First and primarily amongst these would be Generative Design which currently has limited usage in Furniture Industrial Design to Manufacture but has the potential to offer some significant benefits over the traditional processes. It is the foundation for the development of New Products for a new era of sustainable manufacturing in which the next generation of clients will demand customized products over a very short lead time with no need for manufacturing organisations to keep stocks or suffer stock loss costs. As an adjunct to this it has the potential to create complex products, using unconventional construction, with a flat Bill of Materials when manufactured using Additive Techniques. As the design media is digital, decentralized manufacturing becomes far more viable by the transmission of designs to localised production facilities reducing logistics and helping protect potential supply chain vulnerability. The rapid development of Cloud Computing has now put this within reach of many furniture manufacturing organisations and offers far more functionality and creative potential than earlier Shape Grammar based systems. This element has the potential to effectively reduce design cost downstream implications and rework of initial designs concepts by establishing a ‘right first time’ culture with the ability to use the analytic capabilities to reach an ‘Ideal First Solution’ earlier in the design process.

Robot Technology is an allied component in striving to achieve this new strategic manufacturing model as it enables the potential of manufacturing the full-scale generative designs and leveraging their benefits in in tandem with Additive Manufacturing Technologies. Simulation of the manufacturing cell via a GUI also enables a reduction in costs downstream by highlighting any potential problems that may exist pre-production. The freeing of additive manufacturing patents has allowed the rapid development of this approach providing ultimate flexibility while also enabling the use of a large variety of virgin and recycled materials. Skills required to use this technology are also far more flexible and have the potential to move away from specialist ‘product family’ skill sets to be used economically across a diverse range of differing products.

The significant reduction in setup time can lead furniture manufacturing companies towards the realization of a true ‘pull’ on demand manufacturing system (e.g., Just in time (JIT) or Optimised Production Technology (OPT) scheduling and resource planning system) with no stocks or transfer batches and ultimately true one-piece flow affording a greatly enhanced lead time potential.

The above elements have the potential to afford significant benefits in the way products are made, their manufacturing cost and the 'Leagile' nature of that production.

Life Cycle Analysis is the informative final stage in the circular strategic platform to ensure and enable the comparison of products internally and externally in terms of their sustainability and the environmental impact of the products and the organisation as a whole. This information, if used correctly, can feed back into the Generative Design Process to develop an organisational methodology to reduce the environmental impacts of Furniture Manufacturing. It can be used to gauge the benefits achieved by the system improvements or develop Unique Selling Points (USP's). It will serve to highlight the benefits of the new production methods over traditional approaches in many and diverse areas e.g., Hollow matrixed structures reducing materials usage, Homogeneous materials in the product easier to recycle or indeed a flat bill of materials needing no assembly resources etc.

The better informed and educated Client Base will also be driving these changes from an environmental standpoint in the future, but the changes in the disruptive digital technologies tend to be very fast so furniture making organisations need to start researching & preparing now so as not to be left behind.

These Gaps in knowledge once researched, assessed and implemented will potentially have explosive impacts on Design, Manufacturing, Education and Research in Furniture Manufacturing of the future. As Albert Einstein once said, *"We cannot solve problems by using the same kind of thinking we used when we created them".* With this in mind there is a necessity to identify and utilise a novel approach to Inventive Decision Making in the Furniture Industry, which builds upon and compliments existing improvement practices, but forces the developer to examine overall system performance. The compound benefits of this type of analysis have the potential to far outweigh those of examining the component parts individually. To this end TRIZ will be used as a guiding methodology for the examination of the Furniture Sustainable Generative Design to Manufacturing platform.

3. Robot Additive Manufacturing Customisation

3.1. Identification of problems & conflicts using TRIZ

The TRIZ approach to problem solving and the identification of original solutions is ideal for application in the UK Furniture Industry, which is renowned for its conservative mindset. In order to assess all the elements covered in the Literature Review and exploit their potentials for the future of Robot Based Additive manufacturing of Generative Designs it is essential to have a framework to assess these elements while also identifying uses currently under development in different spheres of manufacturing. To this end the use of TRIZ to identify, assess and transform these elements for use in furniture manufacturing is essential. The TRIZ tools will lead both Manufacturers and Designers through a clear process of Research and Development to leverage the benefits of the technologies being examined.

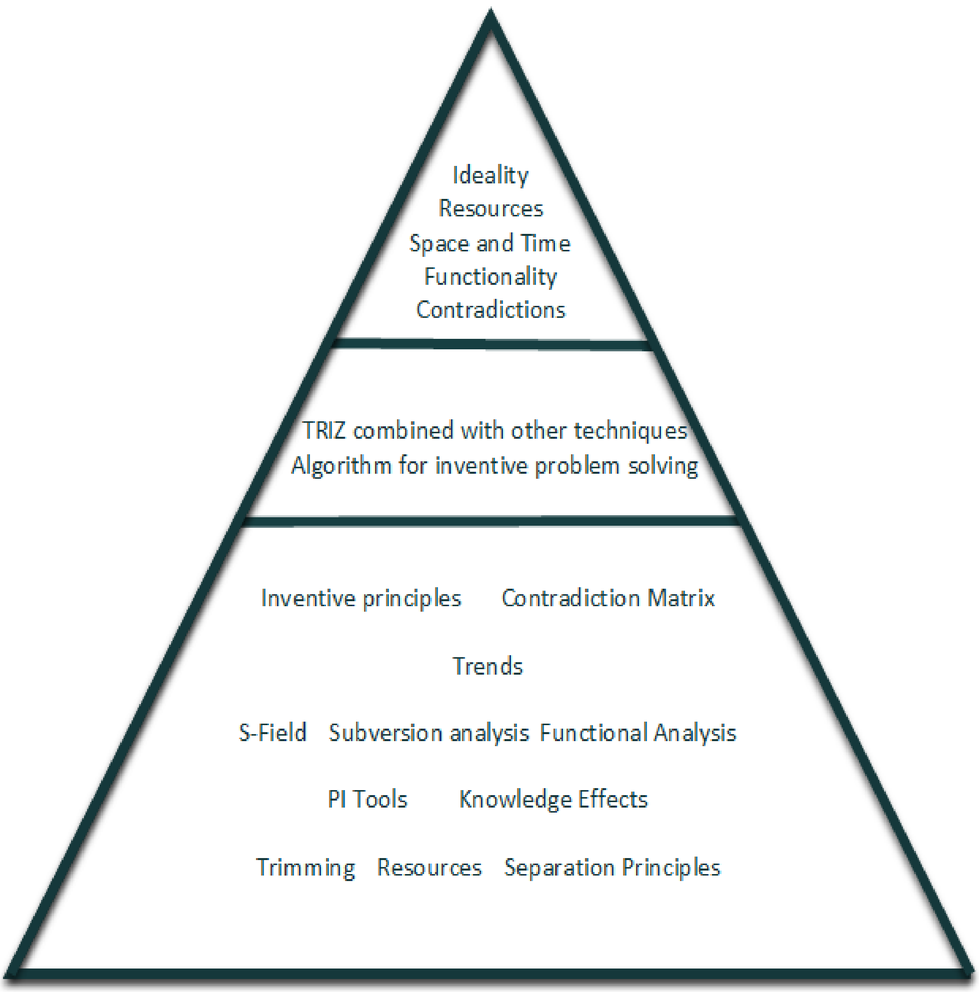


Fig. 14 TRIZ Elements, TRIZ Journal.

TRIZ is not a new technique and has been in existence for around 50 years and was developed by inventor Genrich Altshuller. It used predominantly in academic exercises and very rarely in furniture product and technology design. However, Six Sigma and TRIZ are excellent partners as each method has different strengths and focuses which complement and enhance each other.

Given a failing or inefficient process Six Sigma methodology is an excellent tool for delivering outstanding improvements. Design for Six Sigma (DFSS) goes further and examines the introduction of new products and Services, but still does little to add creative problem-solving solutions.

TRIZ does not eliminate work and effort in the generation of original ideas, but it does bring a level of discernment and thought goading coherence to the creation and investigation of innovative solutions.

TRIZ is not only about the solving of physical and technical challenges but can in fact be used on almost any problem or scenario. TRIZ can be used as a whole or in part to enable creative problem solving and innovation. It deals with patterns of technological innovation, systems thinking, contradictions, inventive principals and the identification of idle resources to overcome psychological inertia.

3.2 TRIZ Design for Six Sigma Lean Manufacturing

The aim is to reduce the conceptual and operational vunerabilities in the design process. Six sigma in all its forms has a basic requirement that all elements are within six times the standard deviation on each side of the specification limits.

This basic premise is applied to the Critical To Quality (CTQ) elements of the product, these have been examined critically using a number of different approaches such as Taguchi's Robust Design Methodology and also Six Sigma Design, Measure, Analyse, Improve and Control (DMAIC).

On the other hand concept issues have been largely overlooked due to many factors including:

- Lack of systematic analytical tools to identify optimum solutions
- Lack of designers knowledge
- Pressure of deadlines and schedules

This lagging philosophy of Design leads to a situation where ‘firefighting’ is the normal state.

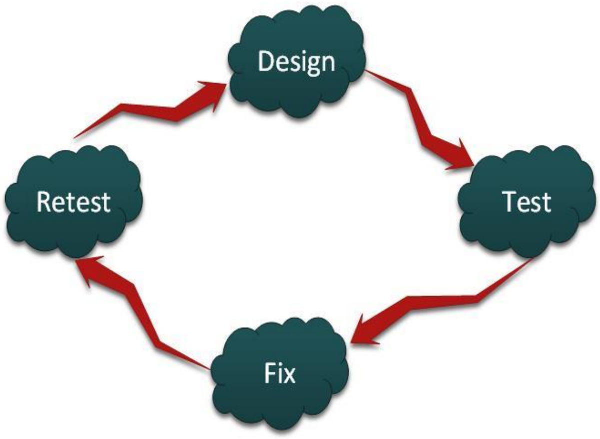


Fig. 15 DFSS aims to reduce ‘Firefighting’ (Fox.A,2020)

The implementation of Design for Six Sigma at the concept stage should be a major goal of organistions to make the process more streamlined and forward loaded. Many Furniture Designers lack the knowledge to be able to apply scientific design methodology and rely quite heavilly on subjective decision making. By using the front loaded approach the emphasis shifts towards more abstract problem solving at the early stages of design to ultimately achieve prevention rather than ‘firefighting’.

Six sigma is so often focused on the process that the wider view of the System is missed. It is also usually focused on one Critical to Quality (CTQ) Issue to avoid conflicts. Design for Six Sigma (DFSS) deals with multiple CTQ’s but are often resolved with significant trade-offs. DFSS often attempts to use more and more statistical methods to try and balance opposites. The use of Contradiction Identification and Removal may significantly reduce the amount of work necessary.

Where FMEA is used in DFSS, TRIZ may be able to simplify the dilemma with the application of inventive and separation approaches to resolve conflicts.

Quality Function Deployment (QFD) House of Quality is assistive but does not generally follow contradictions through to a timely and innovative solution. Although the roof of the house is really all about conflict.

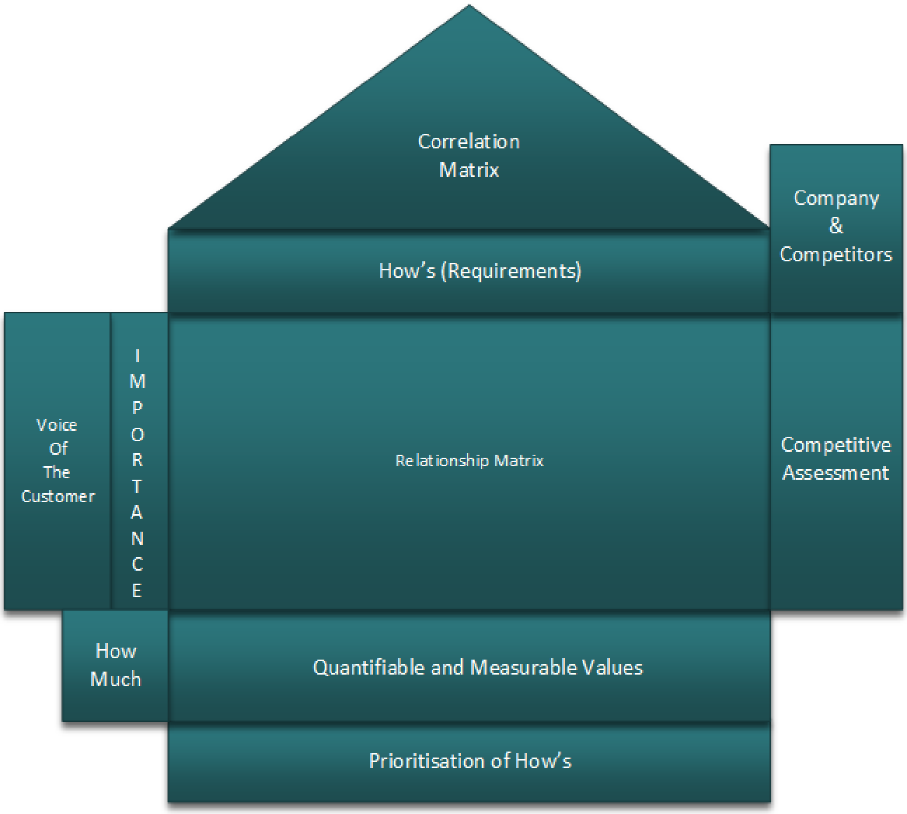


Fig. 16 Illustration showing the Elements of Quality Function Deployment (QFD)

Six Sigma benefits TRIZ in that it is a far more business orientated method. TRIZ lacks the techniques to realise efficient practical benefits from the innovations created.

Tasks are often performed by fast recognition of shapes and patterns combined with mental retrieval of facts. The human minds' ability to do this is so strong that often we see things that are not there by inference. These mental processes are so fast and strong they can impair the ability to be creative.

In many craft-based industries, including Furniture, creativity and design innovation are often unsystematic following instances of inspiration & revelation. The innovation process to a large degree follows repeatable patterns and trends which have been documented in detail. It follows that future developments will also follow the same patterns but in different applications.

Innovation works to its best effect when the entire system which affects the problem is considered in its solution. This also helps to identify hidden resources and the overall functionality of the System.

Six Sigma uses DMAIC as a method of examining and solving issues. TRIZ has a similar method known as ARIZ to guide one right through the creative and innovative process.

Contradictions are a key component of TRIZ where it is assumed that to truly be creative and innovative the solution must solve at least one Contradiction. Rather than accepting a compromise TRIZ advocates solving the Contradiction allowing both states or features to co-exist.

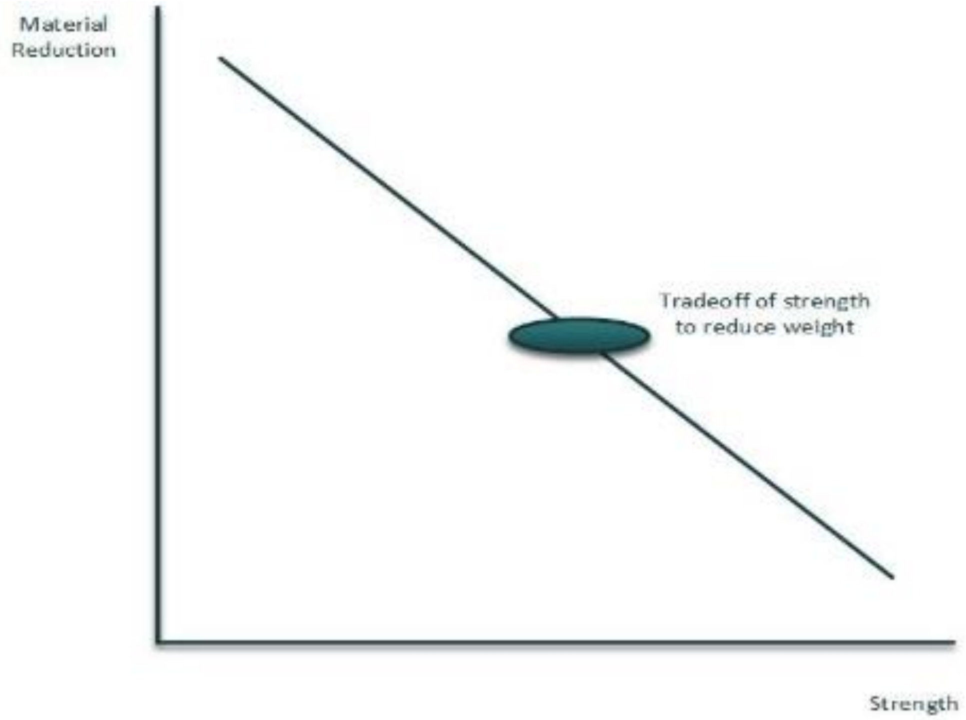


Fig. 17 Illustrated example of Design Compromise

Unlike other methods TRIZ starts with the Ideal Solution (IFS) that provides maximum benefit with zero increase in cost and harmful effects. This is in stark contrast to Six Sigma where one starts with the existing circumstances and progresses forwards from that point.

Identification and addition of unused resources can be added into the system to give benefit in alternative ways without adding cost to the overall process.

Inherent in the TRIZ methodology are the 40 Inventive Principles (IP) that others have used to solve contradictions in the search for inventive solutions. These distillations of good practice have been further distilled into a Contradiction Matrix indicating the most common intellectual properties historically used to solve a pair of engineering conflicts.

The Contradiction Matrix is an ideal place to start for the generation of solutions, especially where contradiction exists between one or more elements. It is an efficient way of identifying the best intellectual properties to use on a particular problem, but always considering the rest for the optimum solution.

Worsening Feature → / Improving Feature ↓	Speed	Shape	Loss of Time	Reliability	Measurement accuracy	Ease of operation	Adaptability or versatility	System complexity	Measurement Difficulty	Productivity
Speed	+	35, 15, 18, 34		11, 35, 27, 28	28, 32, 1, 24	32, 28, 13, 12	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	
Shape	35, 15, 34, 18	+	14, 10, 34, 17	10, 40, 16	28, 32, 1	32, 15, 26	1, 15, 29	16, 29, 1, 28	15, 13, 39	17, 26, 34, 10
Loss of Information	26, 32		24, 26, 28, 32	10, 28, 23		27, 22			35, 33	13, 23, 15
Loss of Time		4, 10, 34, 17	+	10, 30, 4	24, 34, 28, 32	4, 28, 10, 34	35, 28	6, 29	18, 28, 32, 10	
Measurement accuracy	28, 13, 32, 24	6, 28, 32	24, 34, 28, 32	5, 11, 1, 23	+	1, 13, 17, 34	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	10, 34, 28, 32
Ease of operation	18, 13, 34	15, 34, 29, 28	4, 28, 10, 34	17, 27, 8, 40	25, 13, 2, 34	+	15, 34, 1, 16	32, 26, 12, 17		15, 1, 28
Ease of repair	34, 9	1, 13, 2, 4	32, 1, 10, 25	11, 10, 1, 16	10, 2, 13	1, 12, 26, 15	7, 1, 4, 16	35, 1, 13, 11		1, 32, 10
Adaptability or versatility	35, 10, 14	15, 37, 1, 8	35, 28	35, 13, 8, 24	35, 5, 1, 10	15, 34, 1, 16	+	15, 29, 37, 28	1	35, 28, 6, 37
System complexity	34, 10, 28	29, 13, 28, 15	6, 29	13, 35, 1	2, 26, 10, 34	27, 9, 26, 24	29, 15, 28, 37	+	15, 10, 37, 28	12, 17, 28
Productivity		14, 10, 34, 40		1, 35, 10, 38	1, 10, 34, 28	1, 28, 7, 10	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	+

Fig. 18 Contradiction Matrix, The TRIZ Journal, 2009

Altshuller identified the fact that many similar solutions crossed industries creating benchmarks for further innovation elsewhere.

Patents are a safeguard from a government to an inventor, allowing that individual to profit from their unique work. Patents are for a limited time period and must be documented in sufficient detail to allow another appropriately skilled individual to reproduce the invention.

From his research Altshuller further divided inventive outcomes into 5 categories.

Level	Inventiveness	Solutions	Knowledge Base
1	Solution Apparent	32%	Team/Company
2	Minor Improvement	45%	Industry
3	Major Improvement	18%	Across Industries
4	New Concept	4%	Widespread
5	Discovery	1%	All that’s knowable

(Mulberry Consulting, 2003)

Levels 1 & 2 are similar to simple Six Sigma Process improvements, whereas 3 & 4 are more closely related to Design for Six Sigma adding value to both the project and the business.

3.3 TRIZ Techniques and approaches for Lean Manufacture

ARIZ (Algorithm of Inventive Problem solving)

- **Define**
- **Select Tool**
- **Generate**
- **Evaluate**
- **Use**

TRIZ is a very powerful standalone technique, but the selective use of tools from both TRIZ and Design for Six Sigma can produce a highly productive and innovative hybrid approaches tailored to each individual application.

TRIZ can be very useful at the ‘Define’ Stage of DMAIC using the ‘Ideal Final Solution’ and at the ‘Improve’ stage using the Contradiction Matrix enhancing ‘Brainstorming’ initiatives. Conflict at the ‘Measurement’ stage can use TRIZ techniques to overcome challenges.

Quite often consciously or unconsciously we try to divide product design projects into time phased segments. This can be done formally using tools such as Multi Generation Planning (MGP) which is mainly used to break down the project into easy to handle sections. It does not really assist one to examine the problems from a new standpoint.

The TRIZ Nine Screens approach is a technique for breaking the project down by system and also by time to examine different perspectives as we move through the segments and also examine their interrelationships.

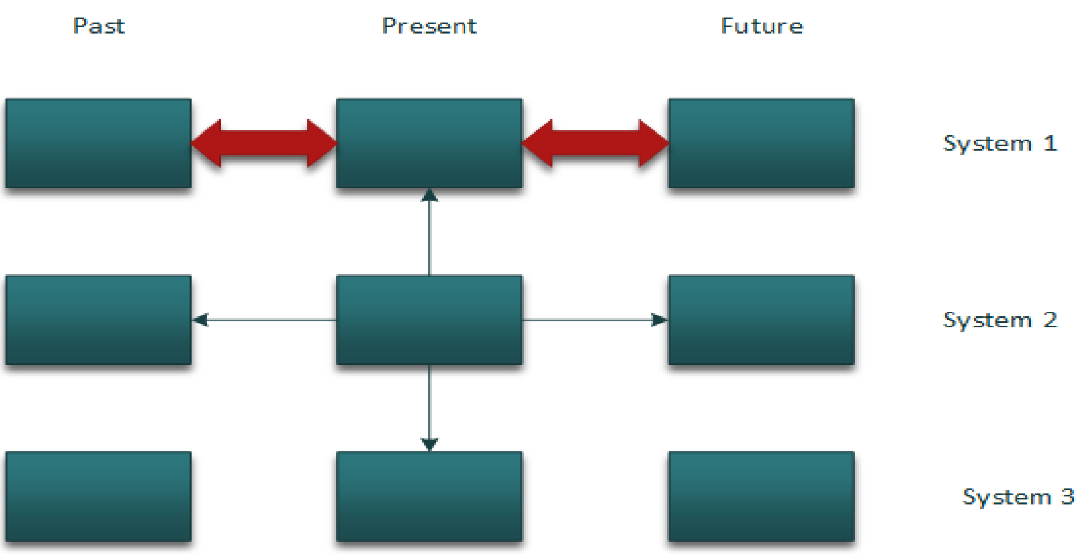


Fig. 19 TRIZ Nine Screens Technique

The main aim of this technique is to move towards ‘Ideality’ by removing things from the system (reducing cost & harm) and adding others (increasing benefits & value).

Using TRIZ Tools & Objects problems can be reduced to the very basic factors and be regarded as ‘Objects’, ‘Tools’ with ‘Forces’ acting upon them (positive and negative) to change their characteristics. These can be hard physical tools or ‘virtual tools’ used to change something.

This technique can be useful for identifying characteristics such as:

- Discovering all elements of the system
- Useful and harmful attributes and the trade-offs behind them
- Critical Features associated with each element
- Element purposes, operating environments and their confines

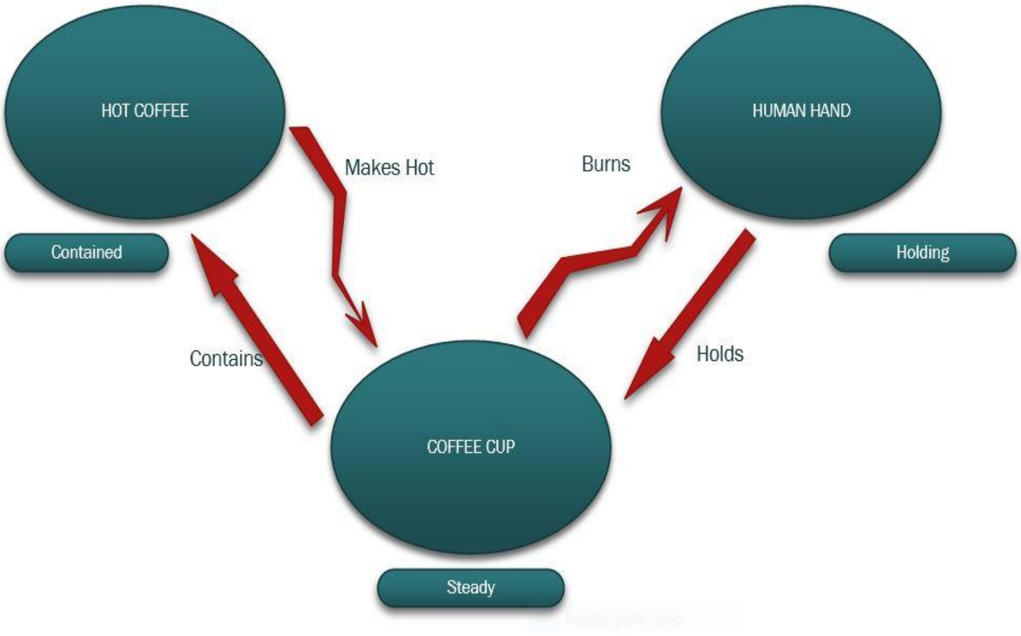


Fig. 20 Coffee Cup Example of Objects, Tools and Forces

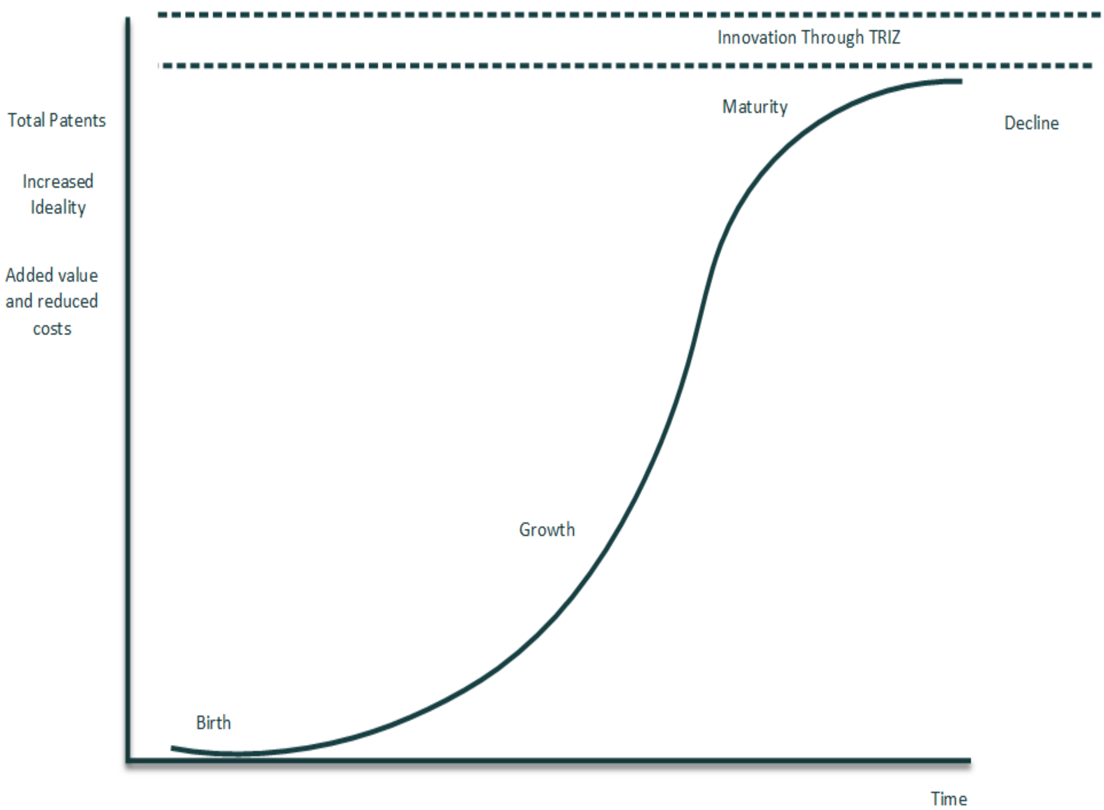


Fig. 21 Trends of Evolution S – Curve, Pattern of Evolution, The TRIZ Journal

There are many evolutionary change areas that could be considered. The focus here will be those which offer the best opportunities for the promotion of Innovative Furniture Products and technological advancements.

Using Simplification and Trimming the larger overall system in which our objects exist can be analysed to identify how better functionality can be integrated and how better results can be delivered with fewer parts or processes.

Segmentation may also be employed and is a very powerful technique for problem solving. It can be applied at many levels from large solid objects to Voids and Vacuums at the extreme and can even encompass Time as an element for segmentation of the product or process.

- Surfaces - 2D
- Objects - 3D
- Time - 4D
- Orientation - 5D

The above concepts of Space, Time and Interface (STI) are very important in the TRIZ approach to problem solving. The evolutionary trends illustrate the significance of having more interfaces for interaction between multiple components or systems to empower innovative design processes.

Geometric Change which is a key attribute of AI based Generative Design is a very interesting collection of trends that advocate the increased use of asymmetry, the reduction in boundaries and pure geometric change to increase the idealism of products. Traditional automated manufacturing is very well suited to symmetrical products. Increasingly with the development of more intelligent processes and smarter materials the value of asymmetrical design is being appreciated for its better interface to Human requirements. Generative Design combined with Additive Manufacturing are a very good systems process example.

The fast-moving Environmental Impact requirements are trending towards smarter & more user-friendly materials. This combined with a very real concern for the environmental nature of new materials is affecting the way we look at product and process design.

Innovative design is moving away quickly from the traditional passive product offerings to those which interact more fully with the user. The use of Human senses of Taste, Smell, Sight, Hearing and Feel/touch are becoming inherent in the new innovative design processes employing Artificial Intelligence to create unique solutions.

Many traditional designs began as largely static in nature. With many options for control, automation and shape/property changing materials the scope for designers has become so much more dynamic. These evolutionary developments open up the opportunity for innovative products which are far more co-ordinated and integrated with smart control over multiple axes.

Design methodology and approach is a powerful process of problem solving that begins with understanding unsatisfied customer needs. From that insight emerges a process for innovation that encompasses concept development, applied creativity, prototyping and experimentation. When design thinking is applied to business, the success rate for innovation improves substantially.

Design methods themselves are emerging that remove the human subjectivity from a number of areas and replace it with vigorous optimisation, FMEA & human interactive simulation, resulting in higher levels of customer satisfaction. This automation has moved forwards considerably to not only replace human effort but to also contribute to elements of the human thinking processes. In some ways these trends seem to follow Maslow’s Hierarchy of Needs.

Fig. 22 Abraham Harold Maslow, 1908 – 1970

Given a problem one of the best ways to resolve it is to separate it from everything else with which it conflicts. This approach has been developed by TRIZ into four main techniques or approaches:

- Space – *Ask Where*
- Time – *Ask When*
- On Condition – *Ask If*
- By Transition – *Look at Evolutionary Trends or Changes in Perspective*

In TRIZ each of these four strategies is linked to a number of Inventive Principles and it is by the application of those relevant to the problem that an innovative solution can potentially be identified.

'Smart little People' is a fun technique for thinking outside the box. A small army of very intelligent little people who can help you with the problem! They can do anything, they can think for themselves and can work at any conceivable level in the problem without restriction or boundary. These little people can also move about and change position with great ease. You can create scenarios of how a problem may hypothetically be resolved using the little people and their large range of skills and attributes.

One good example of a thought exercise used by physicist James Clerk Maxwell.

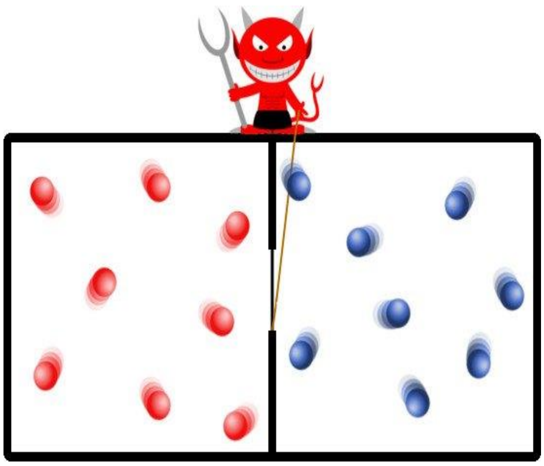


Fig. 23 Maxwells' Demon, Science ABC

This illustration was a thought exercise to illustrate how, hypothetically, the Second Law of Thermodynamics could be broken using the small devil to let fast moving (hot) particles through the gate to a single chamber while blocking the slow (cold) ones. Therefore, heating one chamber and cooling the other.

Pugh Selection may also be used with TRIZ as a technique to gauge the relative merits of several alternatives. The alternatives are judged from a benchmark position and given a rating of:

'+' Better

'S' Same

'-' Worse

Evaluation of the results is a little bit more complex, as it is not necessarily the alternative with the highest number of '+' classifications, but maybe a combination of the other grades that influence the final best choice decision.

	BASE	IDEA 1	IDEA 2	IDEA 3	IDEA 4
Criteria 1		s	+	s	s
Criteria 2		s	s	-	s
Criteria 3		-	-	+	s
Criteria 4		+	+	-	+
+		1	2	1	1
S		2	1	1	3
–		1	1	2	0

Fig. 24 Pugh Matrix (Mulberry Consulting, 2003)

‘Idea 2’ may be the best with ‘Idea 4’ being a close second to it.

In information and knowledge creation there are some design tasks for which no readymade solutions are available that can be extracted from existing sources (ie. Literature Review). These tasks require the creation of new information via research.

- Resolution of technological bottlenecks
- Development of a New Generation of Product
    - Drastically improve product performance
- New Product Marketing Concept
- Technology Push Product Development
    - New Technologies into products

The Lean Product Development Process aims at delivering products with the use of less resources by:

- Thoroughly capturing the Voice of the Customer
- Achieving high product quality and value at the lowest cost using appropriate technology and design solutions

- Continual efforts to decrease waste in the product development process

Toyota identified three key wastes (3 M's)

Muda : non-value added activities (primary focus)

Muri : Overburdened

Mura : Unevenness

Traditional Serial Product Development

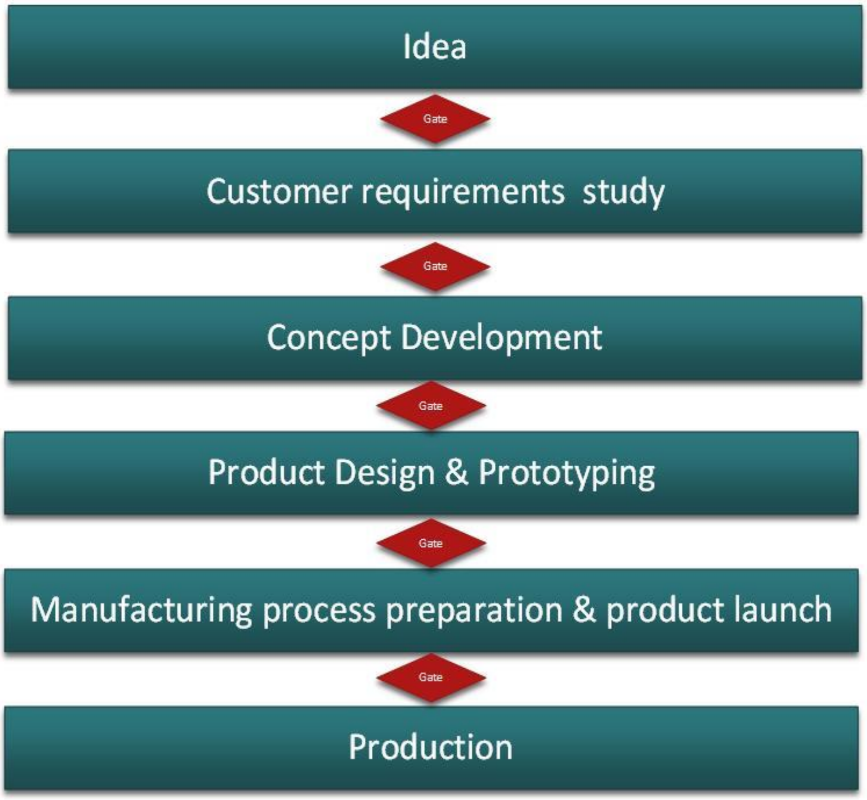


Fig. 25 Improved Parallel Processing of product design phases (Fox.A,2020)

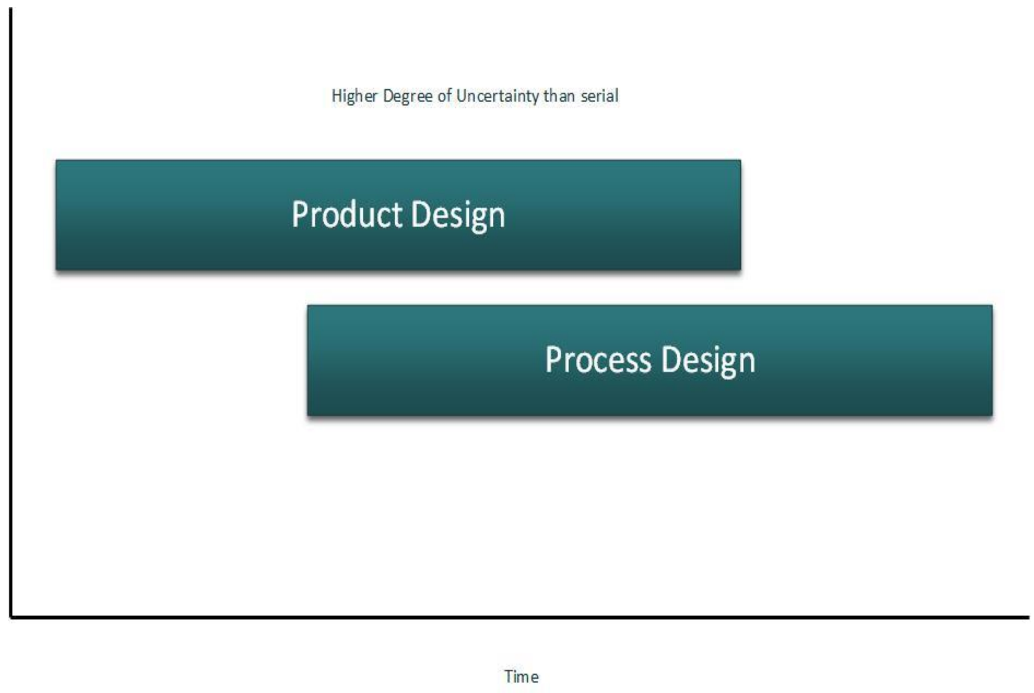


Fig. 26 Increasing value added time in product development (Fox.A,2020)

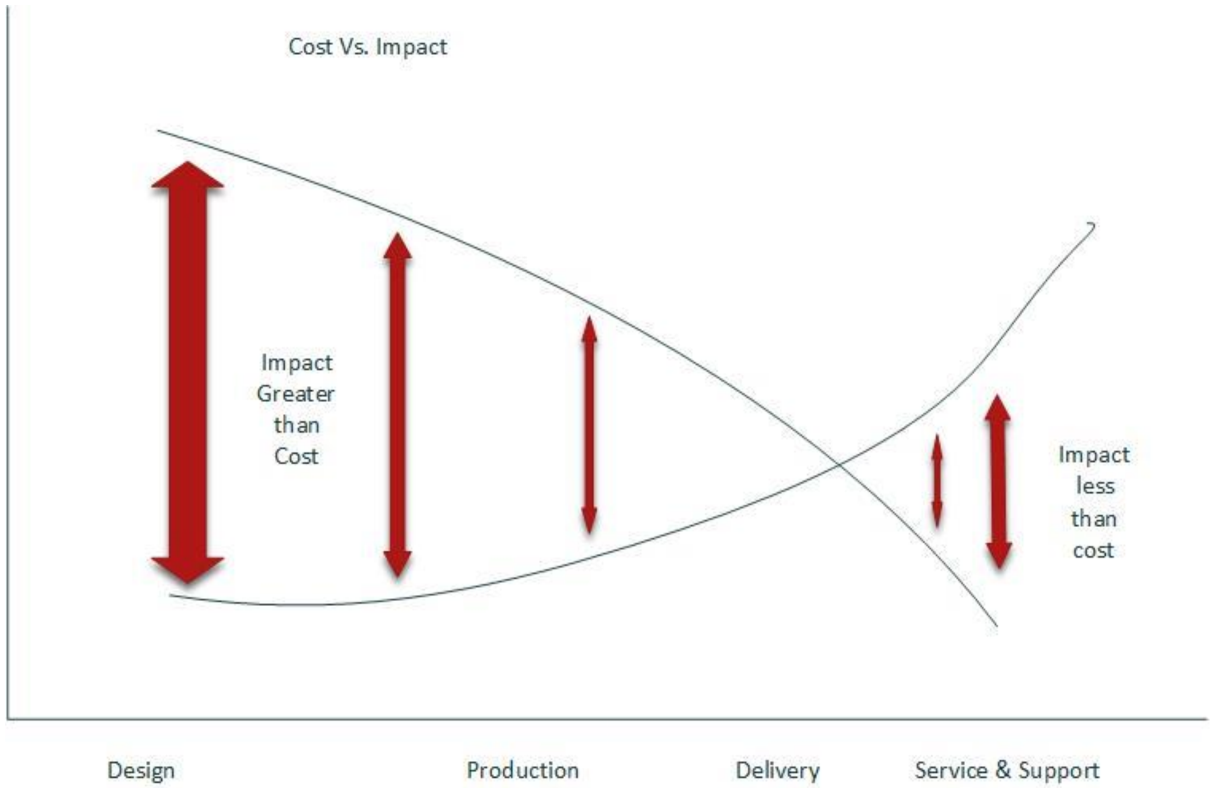


Fig. 27 Process Cost vs. Impact through the product product development lifecycle (Fox.A,2020)

With significant differences in attitudes to value added contributions between cultures and disciplines it is necessary to employ smart structured approaches to design and problem solving, e.g. 1.7 hours of 8 hour day value added to product in Western Companies vs. 4 hours at Toyota (Mascitelli.R, 2002).

Some working practices identified to increase efficiency are :

- Focused working time on one project without constant switching & no interuptions. These are two key elements to increasing design productivity.
- The waste and inefficiencies related to creating product designs can be tackled in a number of areas by smoothing the product development flows using Queuing Theory :

- Inefficient batch queuing
    - Big groups or batches arrive together
- Relationship between capacity and queue length
    - Higher the loading , higher the wait time
- Constant vs variable arrival rate
    - Even loading creates higher throughput
- Uneven vs even job sizes
    - Constant job sizes result in higher throughput

(Mascitelli.R, 2002)

3.4 Management of Information, Knowledge and Communication

Lean production and development is based on the concept of ‘pull’. Information stores can be treated in the same way. With stock of information pulled as required and renewed when expended or when it becomes out of date or an improved product is available.

The advantages of this style of approach are :

- The information is always up to date
- The knowledge is focused enough to service most product development requirements
- The right amount of the current information is available when needed

The information stored may consist of :

- Virtual design information and specifications
- Reviews and visual information
- Simulations and results
- Knowledge database and previous discussions
    - Best practice
    - Quality issues
    - Recommended Quality Standards & specifications

The product design process is an information and knowledge generation activity, 'set based' design is very advantageous , where the design process is front loaded with information at the conceptual stage where there is still maximum space for design movement. This approach is used mainly in modular design where independent components are joined together to form sub-systems using common interfaces. Therefore each sub-system can be worked on in parallel. These parallel activities can include the use of information from a number of sources:

- Current Knowledge
- New technology from R&D activities
- New information through Brainstorming or TRIZ

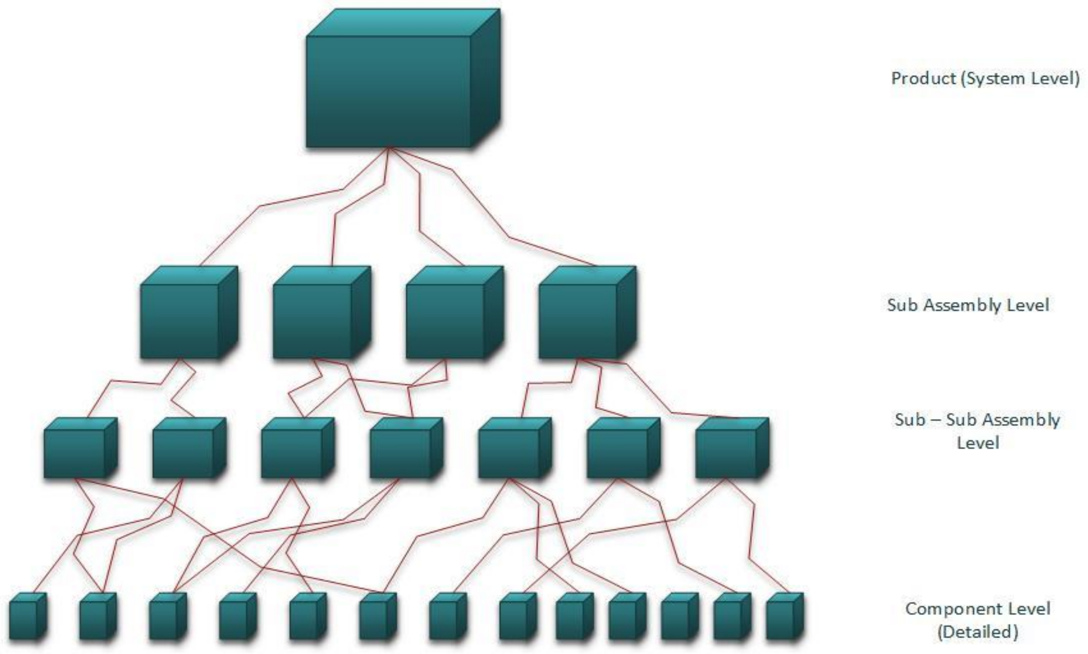


Fig. 28 Parallel problem solving at different levels of the B.O.M. (Fox.A,2020)

In order to make these forms of development effective and ensure the maximum value added activity, it is important to capture data and communicate issues efficiently.

The use of A3 Reporting is an element of 'visible knowledge' for the capture and efficient communication of progress information. This is a simple concept where the current status is displayed on a single sheet of A3 paper. It may include the following:

- Problem Statement
- Advances / Setbacks
- Prior research undertaken
- Root cause analysis
- Activity method statements
- Data Analysis
- Recommendations

They can be used in a number of different tasks:

- Sharing of knowledge
- Problem solving
- Project status report
- Fast tracking information to members prior to project meetings
- Disseminating information on a Planning Wall

The main objective for Design for Six Sigma is to 'Design it right first time'

3.5 Agility and Mass Customisation

Agile Manufacturing represents a very interesting approach to developing competitive advantage in today's fast-moving consumer led markets. A strong focus is placed on rapid response to customer demand. This allows the organisation to take advantage of small windows of opportunity and react to fast changes in end user demand.

Its key elements are:

- Modular Design
- Exploitation of IT
- Virtual partners & corporate alliances

Prioritisation and growth of knowledge & training in the organisation

Resultant benefits being:

- Instant gratification
- Increased choice
- Retention of Fickle end users who are not loyal to brand

Some of the questions key to adopting Agile Philosophies are:

- Is there a place in this market for a fast delivery adaptation of current products?
- Are there new products concomitant with our skillset that can be re-engineered and personalised for fast delivery?

Mass Customisation has not been seen in its pure form in the Furniture Industry. Benchmark examples of 'Best Practice' from other industrial sectors may be:

- Vistaprint
- Levi Jeans

A Concern with the use of Additive Manufacturing to produce customised products is the proliferation of variation and the end users desire to make more up to date products more often. This may result in the dramatic rise in manufacturing volume and redundant products as consumers find that they can upgrade products instantly and cheaply.

3.6 Summary & Discussion

It is essential for the Furniture industry to break away from conventional decision-making processes to fully evaluate and leverage the potential of new and emerging disruptive technologies. The need to examine and radically adapt developments in other sectors to furniture manufacturing is essential for the future. There are many tools that have been examined in this section which provide a sound foundation for the application of TRIZ analysis to furniture operations to establish greatly enhanced competitive advantage and Unique Selling Points. This framework is easy to use and should be adopted when considering the establishment of future manufacturing strategies. The illustrative nature of TRIZ makes it easy for Furniture Manufacturers to apply it to their operations and see strategic results clearly. The necessity for its application stems from uncertainty in several areas, namely, supply chain security, environmental impact reduction demands and customers' requirements for more and more customised products faster and faster. This framework for future decision making, if correctly applied, makes it easier for companies not to stand still and effectively go backwards.

The core strength of TRIZ is its inventive systems focused approach. It is not a specific business focused manufacturing process improvement methodology, such as Six Sigma, with its specific focus being on issues such as Value Stream Mapping, Issues Critical to Quality and specific Process Performance Improvements etc. It is therefore an incredibly useful tool to set new inventive strategic systems thought directions, which then enable the application of conventional process focused improvement methodologies. This combination of methodologies can realise greater parallel processing to shorten lead times, reduction of costs at the Initial Design Stage, while also encouraging the incremental review and improvement based on historical improvement data. The focus on aggregated systems approaches has the potential in this instance to achieve far greater benefits than conventional analysis and improvement of 'Islands of Automation.'

Employment of TRIZ Tools within this Research, explicitly and implicitly, led to a holistic examination of both elemental and system level elements of the Research. Being qualified in work methods and incentive design in industrial engineering, I am quite well versed with many approaches to process improvement. However, TRIZ tools effectively encouraged a different way of thinking thus guiding the direction and focus of the research disseminated throughout this Thesis.

These tools and approaches enabled a far better identification of the 'Ideal First Solution' encompassed in the Integrated Generative Design and robot based Additive Manufacturing Platform for Furniture. This resulted in research around the consideration of the overall benefits compared to the associated costs and harms of effecting these changes in practice.

This mode of thought led to the examination of Generative Design as a potential method to create novel furniture forms and structures combined with the greater certainty of the designs' characteristics Pre-Production. Leading to a case study examination of the costs related to the execution of these designs via the Robot based additive Manufacturing Concept.

Employing the Nine Screens methodology resulted in the comparison of established Traditional Manufacturing Practices with the proposed new 'Integrated Platform'. The ultimate case study identified a suitable Life Cycle Analysis (LCA) platform in EcoChain Mobius for the comparative estimation of inherent 'harms' of the two manufacturing philosophies while also creating an assessment of the comparative Environmental Impact of each case study product.

This system level comparison led to the need to identify a strategy by which the platform elements were to be integrated and how this would be achieved practically. This requirement by its very nature led onto the need to create a physical Robot Based Additive test cell to help identify the general issues of integration.

It is very clear in the TRIZ approach that the leveraging of patented approaches from other sectors may be of significant interest and could potentially be beneficially adapted, reconfigured & systematically integrated for use in other ways, resulting in aggregated benefits which far outweigh the benefits of each individual element.

Overall, the Research used DMAIC to establish a sound structure by, defining, measuring, analysing, improving and controlling, through integration, key elements of the proposed platform. This is a similar approach to SREDIM used in convention Management Services activities and is effective in achieving a structured outcome.

Use of the forty inventive Principles required some lateral thinking in using the matrix to establish directions for further investigation and creative problem solving. The considerations identified were those of Shape, volume, associated Characteristics together with elements of the Manufacturing process such as Speed, Shape, Ease of Operation, Adaptability & Versatility, System Complexity and productivity etc.

These key areas eventually led to the identification of further areas that were relevant and potentially would have a bearing on the proposed integrated platform development. Some of the areas identified were as follows:

Preliminary actions: To establish something before required and Pre-manufacturing which led to the investigation of Generative Post Design FMEA and its benefit to eliminating downstream manufacturing costs

Dynamic Parts: Examination of the possibility using generative shape grammar to achieve mass customized products.

Change Dimension: Looking further into the future by examining the possibility of changing the print methodology from slicing to a three-dimensional print path to try and eliminate the requirement for support materials and to leverage the strength characteristics of filled polymers.

Continuity of Useful Actions: The way in which the new techniques can strengthen existing methodologies by eliminating waste, encouraging and develop true one-piece flow and achieving manufacturing Agility, thus maximizing value adding stages of the system to the full.

Blessing in Disguise: Investigating the ways in which product and System ‘harms’ can be transformed to ‘good’ in terms of Environmental and Social Impacts. E.g., use of emerging bio and smart polymers to further enhance the benefits of the integrated platform.

Self Service: Research into the idea that enabling mass Customisation in Furniture manufacturing may eventually lead to an increase in ‘Prosumption’ in further reducing waste in terms of time and labor requirements.

Porous Materials: Identification of the possibility to additively print novel structures which unlike current products may have matrixed interiors, thus reducing materials quantities and costs while optimizing strength characteristics.

Homogeneity: Homogeneous materials in one product maximizing the potential for re-cycling and maximizing the development of the Circular manufacturing economy in Furniture Manufacturing.

Disregarding and Recovering: Bio-degradable materials developments to leverage reduction in Environmental Impacts and further encourage recycling.

Parameter Change: Traditional to Generative Design. Traditional Manufacturing to Additive Manufacturing. The growing importance of Environmental Impact. The need for a new strategic way of thinking regarding the adoption of Disruptive Technologies in Furniture Design & Manufacturing.

Composite Materials: For example, the use of filled materials to enhance strength and form, voxcel printing to enable change of characteristics of the materials during the product print process. To leverage these elements, it encouraged the consideration of different methods of additive printing in the future, with the potential development of 3D print paths using the full plethora of digital G-code machine programming functionality as opposed to slicing. (Future Research) In addition to the above focuses, the consideration of S-curve and tool object analysis made one consider the cause-and-effect properties of the system, how each element has the potential to affect the performance of another tool. E.g., The benefit of Generative Design to Additive Manufacturing Potential and vice versa. While also considering the extension of these technologies to enhance the 'Traditional Mature Craft' of Furniture Manufacturing. This activity accentuated the need to evaluate 'Evolutionary Trends' taking place in Manufacturing with its adoption of Big Data real time processing, Cloud Processing, radical developments in materials technology, movement away from 'Islands of Automation' towards dynamic integrated Poly-Systems.

Design Methodology and approach featured heavily in knowledge contribution of this research with the focus on Generative Design and its ultimate economic and sustainable realisation. So, this element of TRIZ was key to the establish a reduction in human involvement and the leveraging of the cloud processing power to develop a new design to manufacturing paradigm which will satisfy a far more environmentally aware market combined with increasing customer demand for fast customised products. The goal in the use of TRIZ is to attempt to create inventive solutions to the overarching research questions and applications, while also attempting to eliminate or reduce conflicts for truly unique solutions. Some of the key areas were, Form vs Function, which is greatly enhanced by potentially unique Generative Solutions, far beyond the scope of human design teams. The issue of manufacturing economics is addressed with Robot Based Additive Manufacturing offering the potential for full scale production, of a wide variety of products, in an economic batch size of one, thus addressing many objectives of the Single Minute Exchange of Die (SMED) approaches. These issues combined with the potential to combine the Integrated Platform with fast moving alternative materials developments, means an even greater for opportunity for future developments in the reduction of the Environmental Impact of Furniture Manufacturing. The stimulation of alternative thinking encouraged by TRIZ for the application of Disruptive Technologies, stimulates one to research an entirely new approach, as apposed to adding 'Islands of Automation' to an existing ineffective system. It helps to expose those potentials of the elements and the aggregated system which are not immediately obvious. The quotation by Buckminster Fuller, the Architect, Philospher & Systems Theorist sums up the potential of TRIZ to reveal hidden systems potentials "There is nothing in a Caterpillar that tells you it is going to be a Butterfly"

4 Chapter 4 Sustainable Generative Design Platform Employing Robot Based Additive Manufacturing

Generative design exists in two basic forms, firstly Shape Grammar driven geometry creation and manipulation. This is achieved through the networking of Algorithms to create the geometry as opposed to the designer drawing these elements. Shape Grammar generative design can also be used to manipulate existing geometry in order to achieve Mass Customised products very quickly.

Recently with the increase in Cloud Processing power and affordability, cloud based Generative Design is being developed for use in many different areas. It is far easier to use then Shape Grammar and it possess great potential to create novel solutions.

Cloud Based Generative Design is an iterative design process that involves a software program that will generate a certain number of iterations that meet certain constraints and a designer who will select and fine tune the feasible iterations by selecting specific outputs or changing the input values, ranges and distributions. The designer learns to refine the program with each iteration as their design goals become better defined over time and is a swift method of exploring design possibilities and manipulating these outputs to form novel results.

4.1 Traditional vs. Generative Furniture Product Design

Despite its name traditional Computer Aided Design (CAD) did very little to aid the design process, it was essentially a way of Creating and annotating accurate geometry which was produced and ordered manually. Even subsequent enhanced versions of CAD only had the ability to evaluate properties of existing designs and edit them through manipulation by the designer. This approach relies very heavily on the individual experience of the designer to come up with novel concepts.

The traditional approach to product design is to create a product that the market wants and then decide how to make it. The profitability of the design was often closely linked to how easy and cost effective it was to manufacture.

'Over the Wall' is a term used to describe a practice where essential elements of the design to manufacturing process work in isolation. Designers who do not have in depth specialist manufacturing process knowledge create concepts and products to try and satisfy market and customer demand in line with a Design Brief. This product concept is then 'Thrown over the Wall' to the Manufacturing Engineers who have in some cases not been involved at all in its development. The Manufacturing Engineers then retrospectively must try and develop manufacturing methods to achieve the product design. Generative Design will be instrumental in reducing this by its ability to analyse the product pre-production and inform the manufacturing engineers, who in turn will have a far more standardised production platform able to cater for a diverse forms and structures using the same basic process. This has the effect of making the design and manufacturing elements far more parallel and far more informed through pre-production analysis.

Generative design is a paradigm shift towards a more collaborative design methodology. Its use of newly available cloud-based computing capability means it can also assess the constraints and criterion of the proposed products, e.g., Materials characteristics, load requirements, costs and manufacturing process capability.

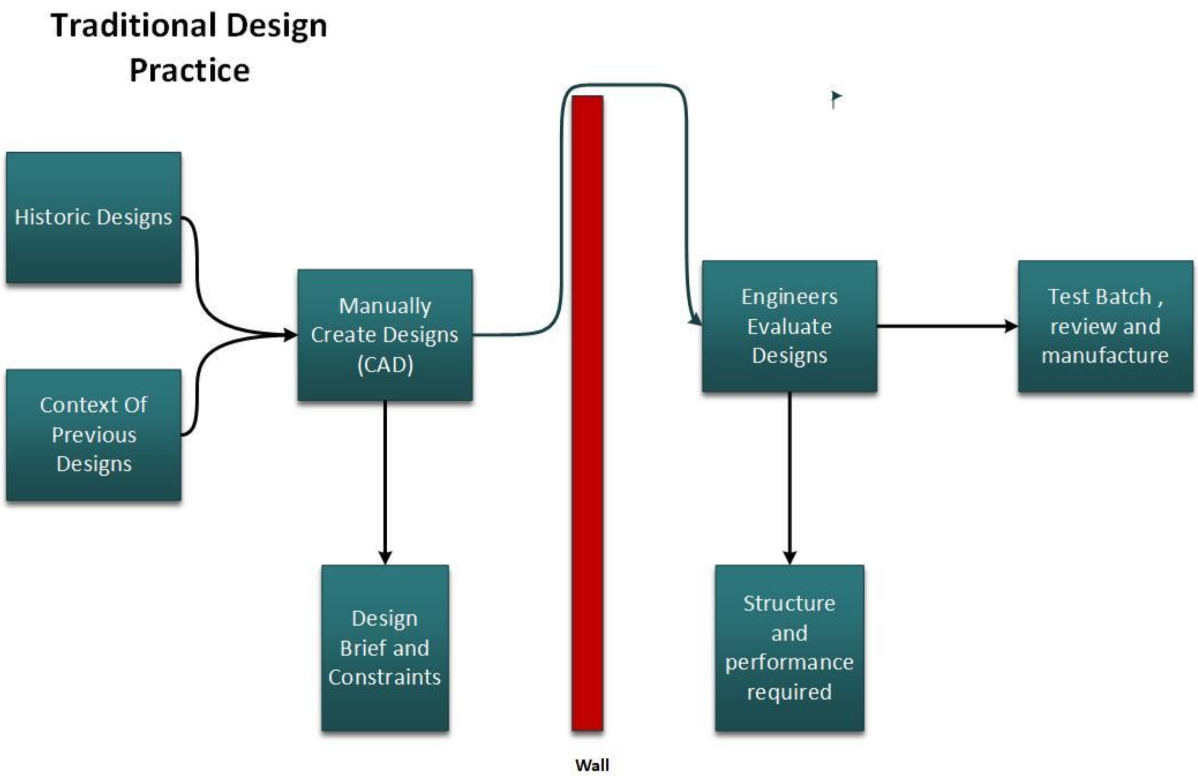


Fig. 29 Process flow of Traditional design (Fox.A, 2019)

Generative Design will be a key element in Industry 4.0 (Fourth Industrial Revolution, 4IR) as it enables organisations to minimise design constraints, be far 'leaner' by reducing waste, increase the cost effectiveness of their manufacturing operations and reduce environmental impacts. In addition to these practical manufacturing considerations

Generative Design also has the potential to significantly enhance design creativity and the USP of new products.

Like 3D printing Generative Design is a disruptive technology creating unique iterations based on criteria including performance requirements and environmental impacts etc. Using these requirements large numbers of design options can be produced which satisfy these ‘rules’. Materials can be optimised significantly and focused to areas where they are required to maximise performance and to minimise waste.

The selected designs can be simulated with multiple virtual end user profiles feeding back data on both effects on the user and the product performance, in effect allowing the product to co-design itself.

The result of this is to produce complex optimised products that would otherwise have been impossible to visualise and manufacture using traditional techniques. As such Generative Design is the perfect aide-de-camp to 3D printing technologies.

The aim is to be able to tell the software what you want to achieve and it produces a range of design options for you. For Example:

Design a Chair to:

- Support maximum weight of 150 kg
- maximum cost of £100
- no more than 10kg of Polylactic Acid (PLA) to be used in manufacture

Based on these simple requirements the virtual supercomputing power can take these criteria and produce numerous options that fit to greater or lesser degrees based on maths that human design technicians could not possibly visualise or create effectively using traditional drafting tools. The creative solutions produced can be very aesthetic & organic in nature and in many cases far beyond human imagination. The human designers’ skills can then be better employed selecting and optimising the best solutions offered by the AI iterations.

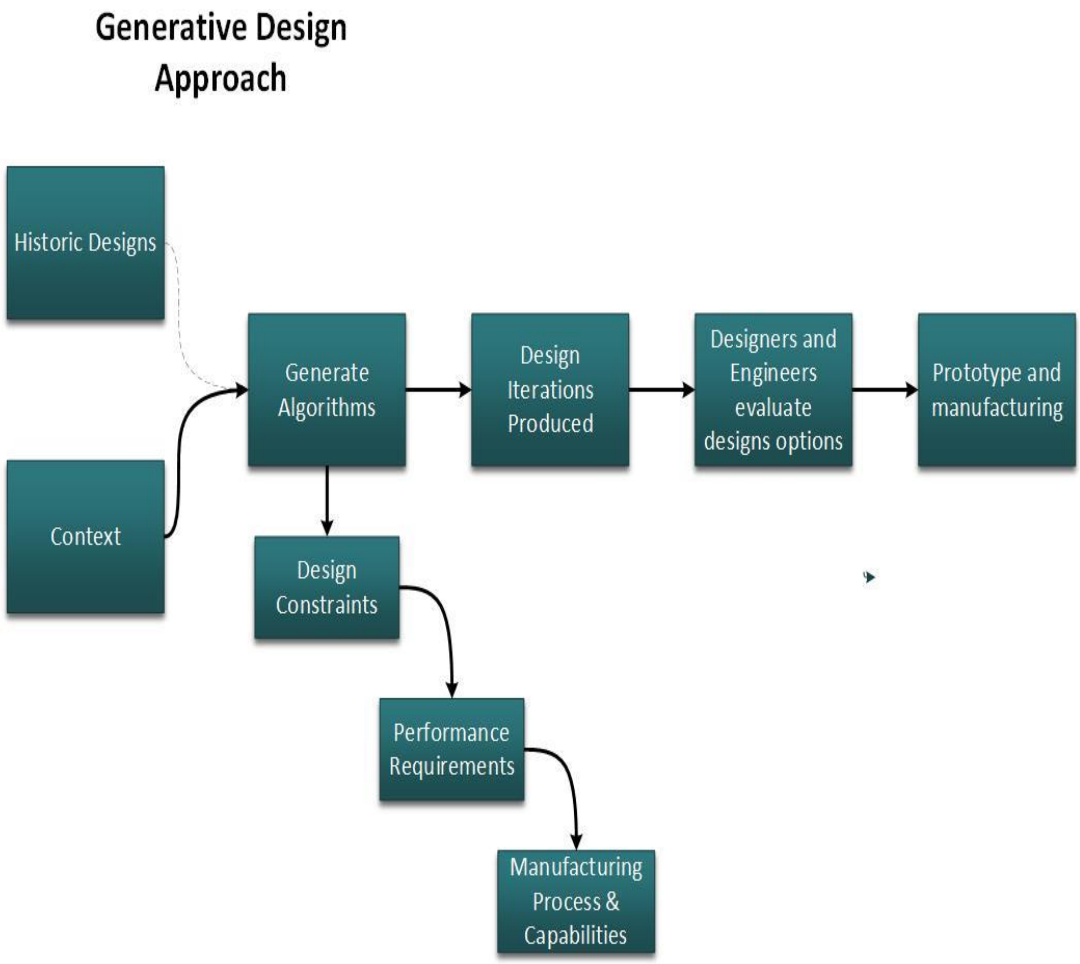


Fig. 30 Generative Design Process flow (Fox.A,2019)

There are a number of fundamental requirements crucial to the successful application of Generative design.

- Trained human operator
- Artificial Intelligence Algorithms
- Cloud Computing Power
- Sound Manufacturing and process awareness

AI Algorithms enable the machines to produce an appropriate response to a situation without prior programming. Quite often resulting in an organic or biomimetic structure which adopts a natural form as opposed to a straight line and geometry based conventional solution.

Generative Design applications such as Autodesk Fusion 360 ultilise Cloud Computing and access 1000's of vacant processors, as an alternative to having to invest in a personal and dedicated supercomputer hardware.

A high Level of Manufacturing awareness is essential with the application of Generative Design as the traditional practice of testing and 'Going back to the Drawing Board' is virtually eliminated using this approach. Traditional optimisation to refine a known solution generally involved removing material without any concrete idea of how something is made or used.

Steps to Generative Design to manufacture.

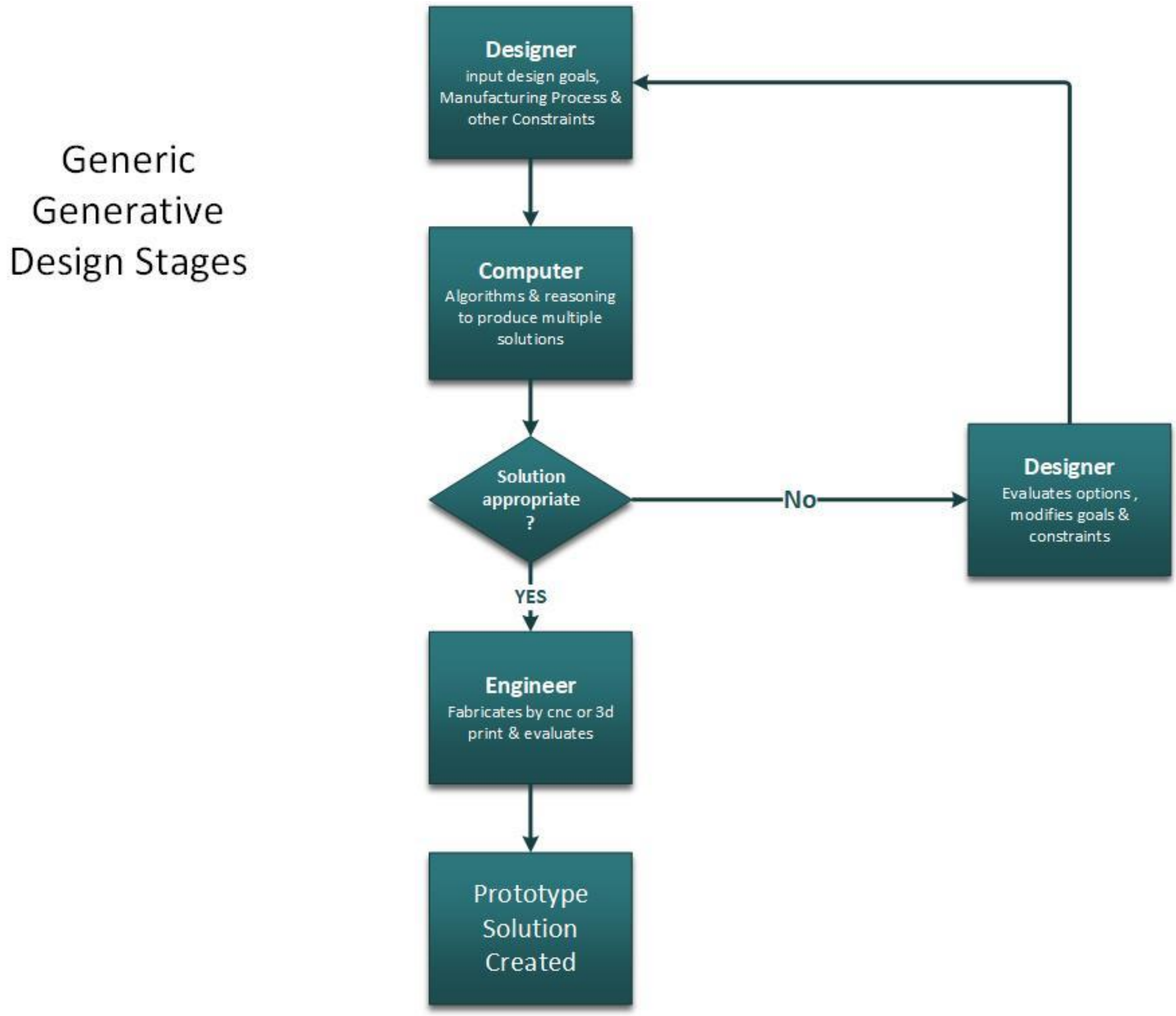


Fig. 31 Alternative strategy employed in Generative Design (Fox.A,2019)

The benefits are:

- A vast array of potential solutions
- Traditionally impossible design geometries possible
- Optimisation to include many other criteria
    - Materials characterisation
    - Manufacturing methods
    - Quite Profound Waste reduction possible
        - Labor
        - Materials
        - Cost
        - Time
    - Environmental Impact
    - Contraction or Design to Manufacturing Lead times

These generative design benefits can be further enhanced by use in conjunction with complimentary and compatible technologies such as:

- Additive Manufacturing Technologies
- New Materials Developments (including 4D)
- Sensors embedded in prototypes for product co-design
- Robots for repeatability & Scale

Manufacturing approaches used in conjunction with Generative Design can further enhance competitive advantage. Software applications such as *'AI Build'* allow cameras to be placed onto the extruder or robot to see the build, when design features do not work it learns from the mistake and creates different strategies for the future. The nature of this type of 'Digital Twin' makes Generative Design and Robot Printing extremely compatible.

The Elbo chair is an example of the creation of a novel form for a chair using a 5-axis machining center and subtractive machining. It illustrates an early realisation that Generative Design had great potential, however the need to produce individual components in separate CNC operations, requiring subsequent assembly and post-processing failed to leverage the full potentials of the approach.

Fig. 32 Elbo chair ,By Arthur Harsuvanakit, 2018

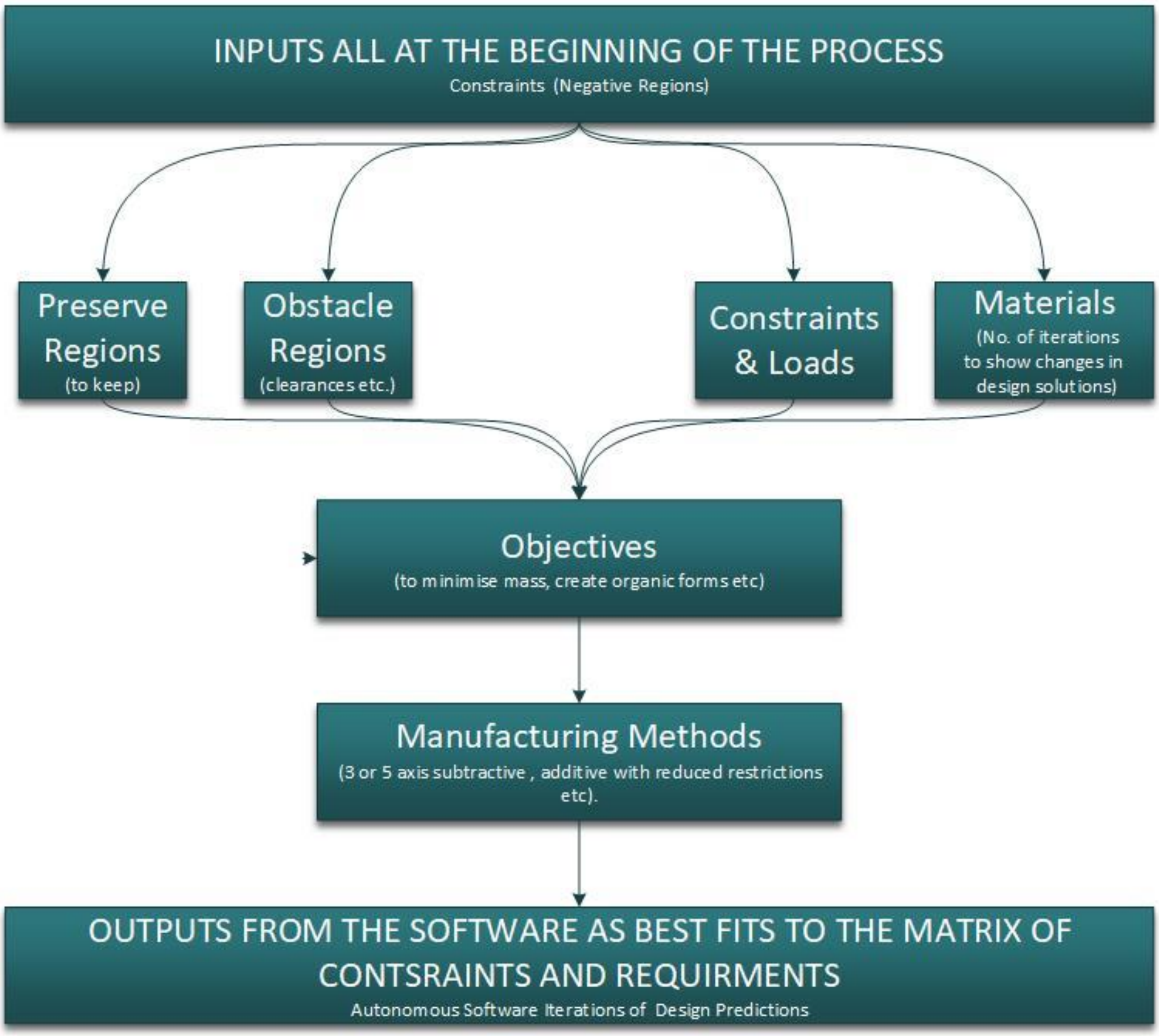


Fig. 33   The necessity to change the 'Design Mindset' for the effective use of Generative Design (Fox.A,2019)

4.2 Shape Optimisation compared to true Generative Design

These are two distinctively different approaches to the optimisation of a product design. For topology optimisation, which may be linked to an objective such as 20% materials reduction etc. The resultant structure is based upon load paths where load is distributed throughout the artefact. Generally, the results of a shape optimisation initiative are not ready for manufacturing and require significant amounts of post processing and remodeling before this phase can begin.

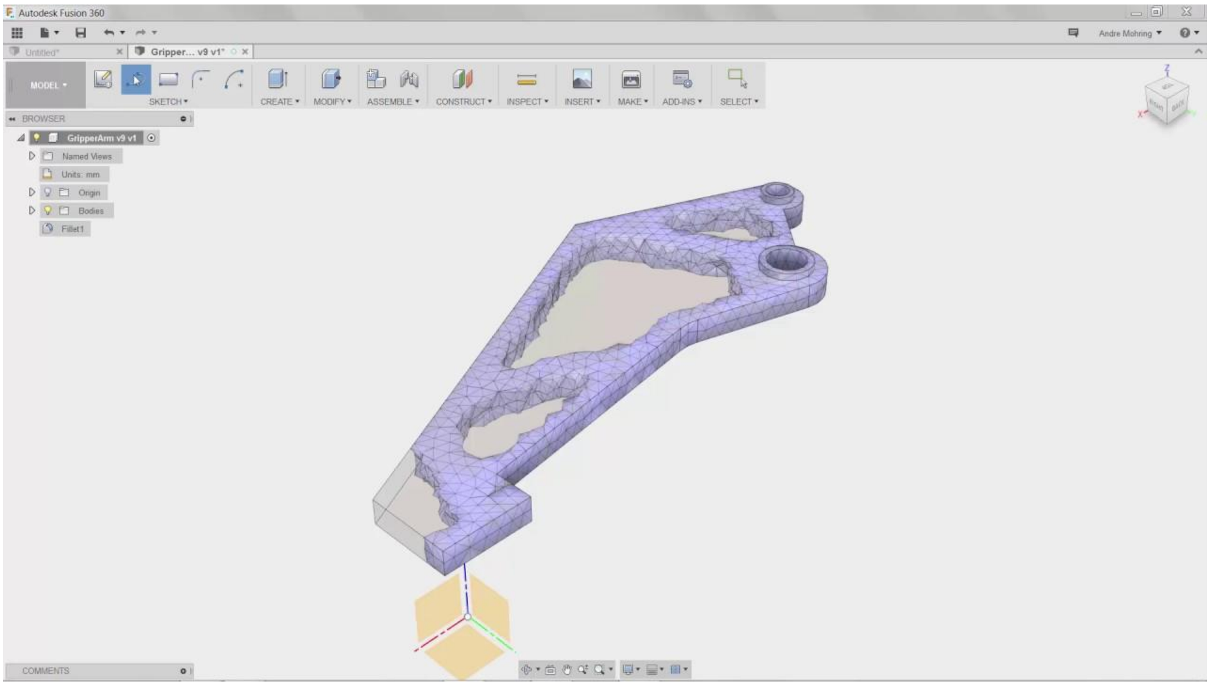


Fig. 34 Shape Optimisation produced using Autodesk Fusion 360 (Autodesk)

In contrast to this using Generative Design preserve and other regions can be specified. The systems will still examine the loading profiles and will make systematic adjustments in material quantities. These adjustments can also consider target factors for safety etc.

This process will continue in different iterations until the solutions converge as best fit solutions to our design criteria. The fact that the software knows where not to go and which features need to be preserved results in a far more machine ready output. So these components or structures can generally go to Additive Manufacturing or CNC machining with the minimum of post processing.

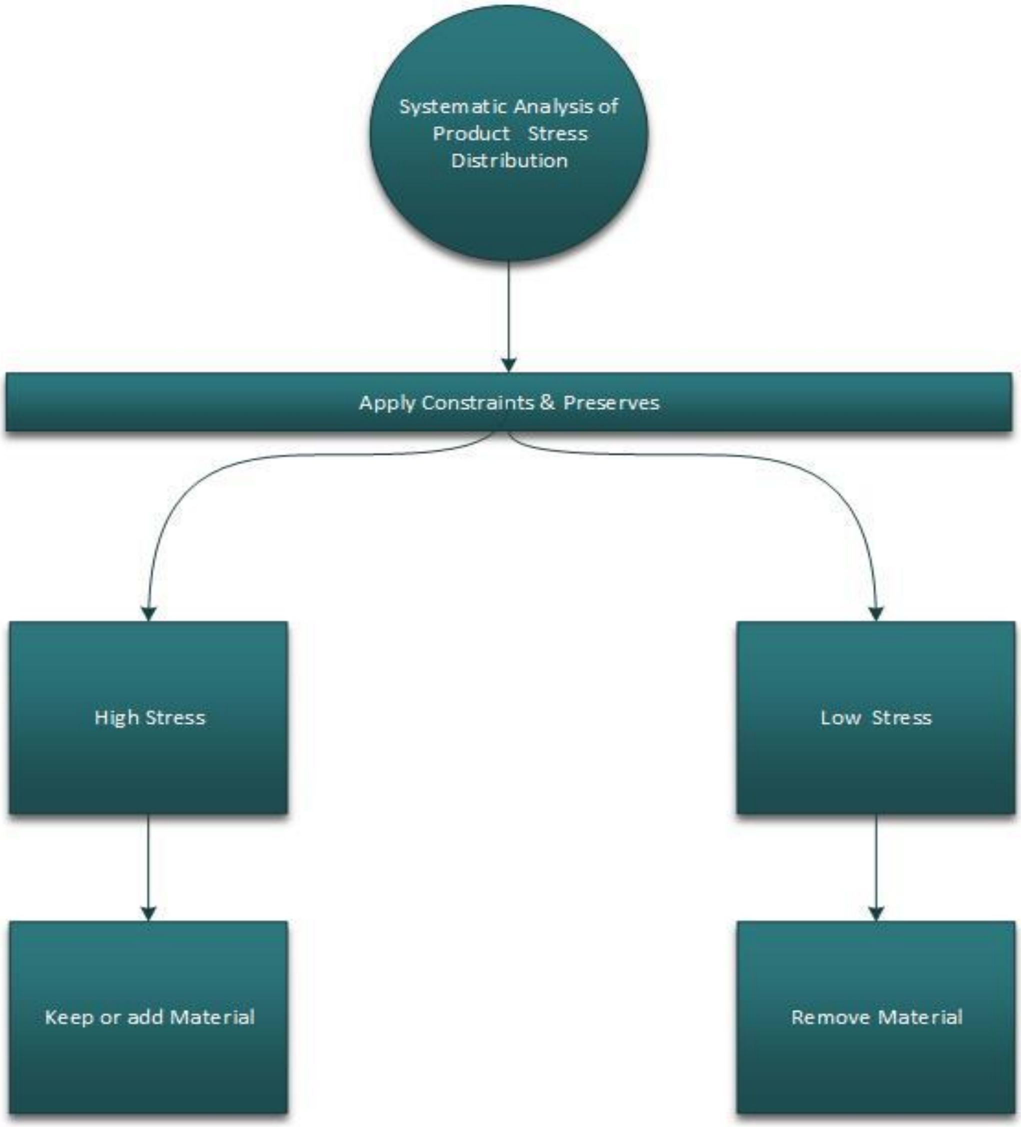


Fig.35 Sytematic analysis & adjustment through constraints and preserves (Fox.A,2019)

The resultant design iterations can be quite organic in nature and may remove internal materials leaving a skeletal structure which satisfies the requirements of the constraints, parameters and objectives defined.

Fig. 36 The Future of Cool! Greatly reduced development time for showcased vintage VW re-engineered Components using Autodesk Fusion 360 Generative Design

4.3 Generative Design for Sustainability

The key advantage of Generative design is its ability to reduce lead & development time in the creation of large numbers of design iterations satisfying the constraints and requirements of the artefact being designed. Sustainability in manufacturing is so important to the future of the growing planet & generative design methodologies have a great deal to offer.

The iterations produced have the potential to offer far better functionality and performance while also potentially delivering less waste in materials and energy consumption. The increased number of design iterations allow human designers to use their skill set more productively in exploring and identifying the best solution from these choices. The uniqueness of the designs also affords organisations the potential for brand supremacy and higher levels of customer confidence.

Generative Designs' integration with Sustainability requirements and constraints allows for the elimination of the 80% of built-in environmental impact at the product design stages.

A fundamental knowledge of the core competencies is at the heart of rule based Generative Design and are based in the following areas:

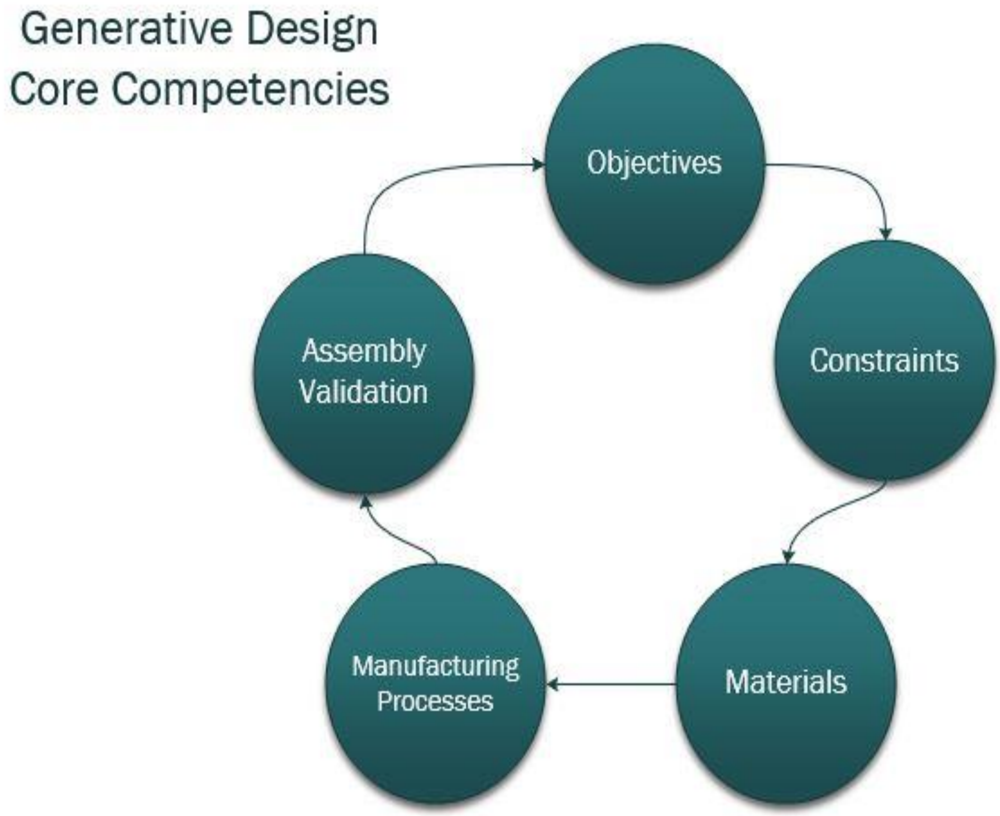


Fig. 37 The core areas of competency required for Generative Design (Fox.A,2019)

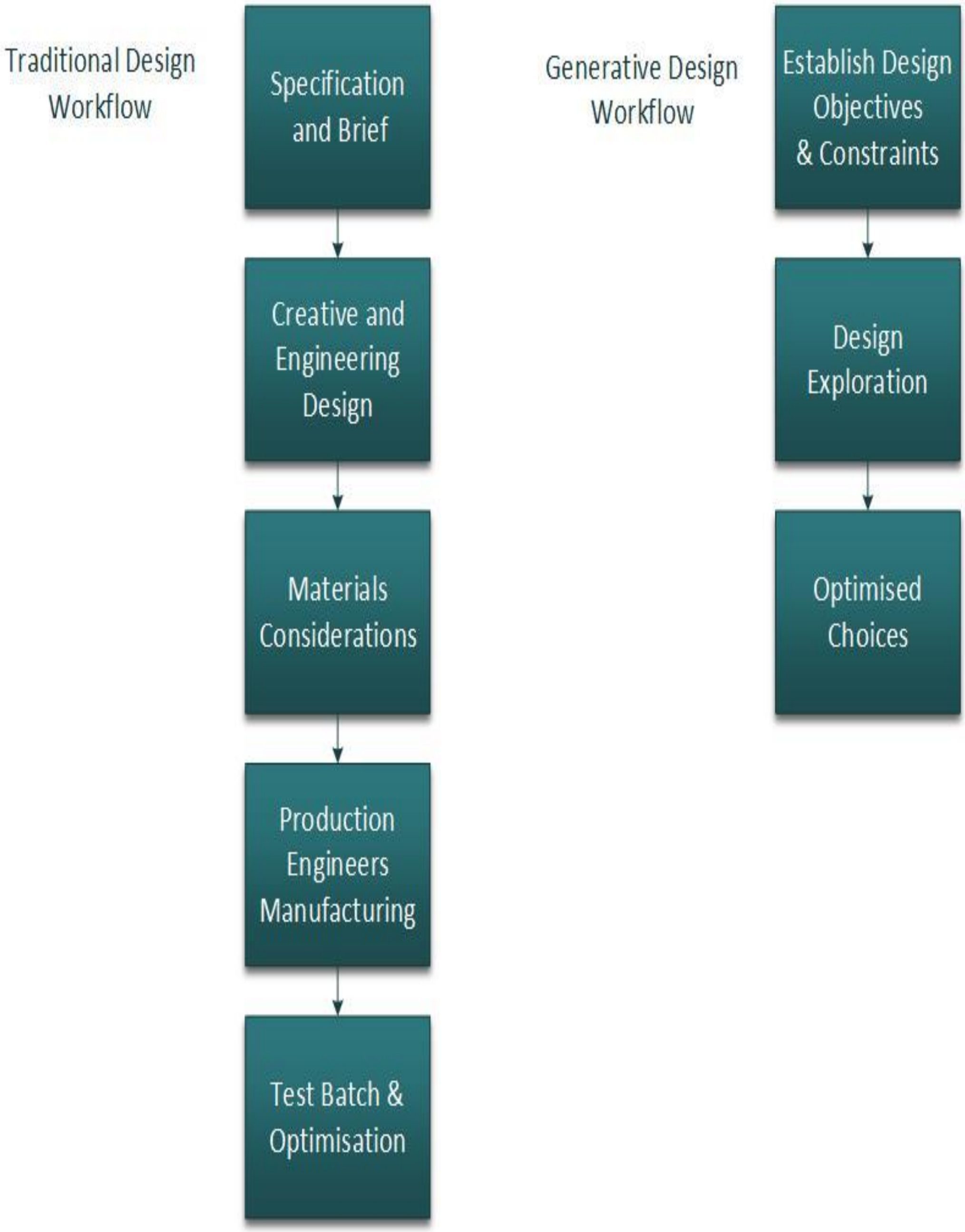


Fig. 38 Traditional Vs. Generative Design workflows (Fox.A,2019)

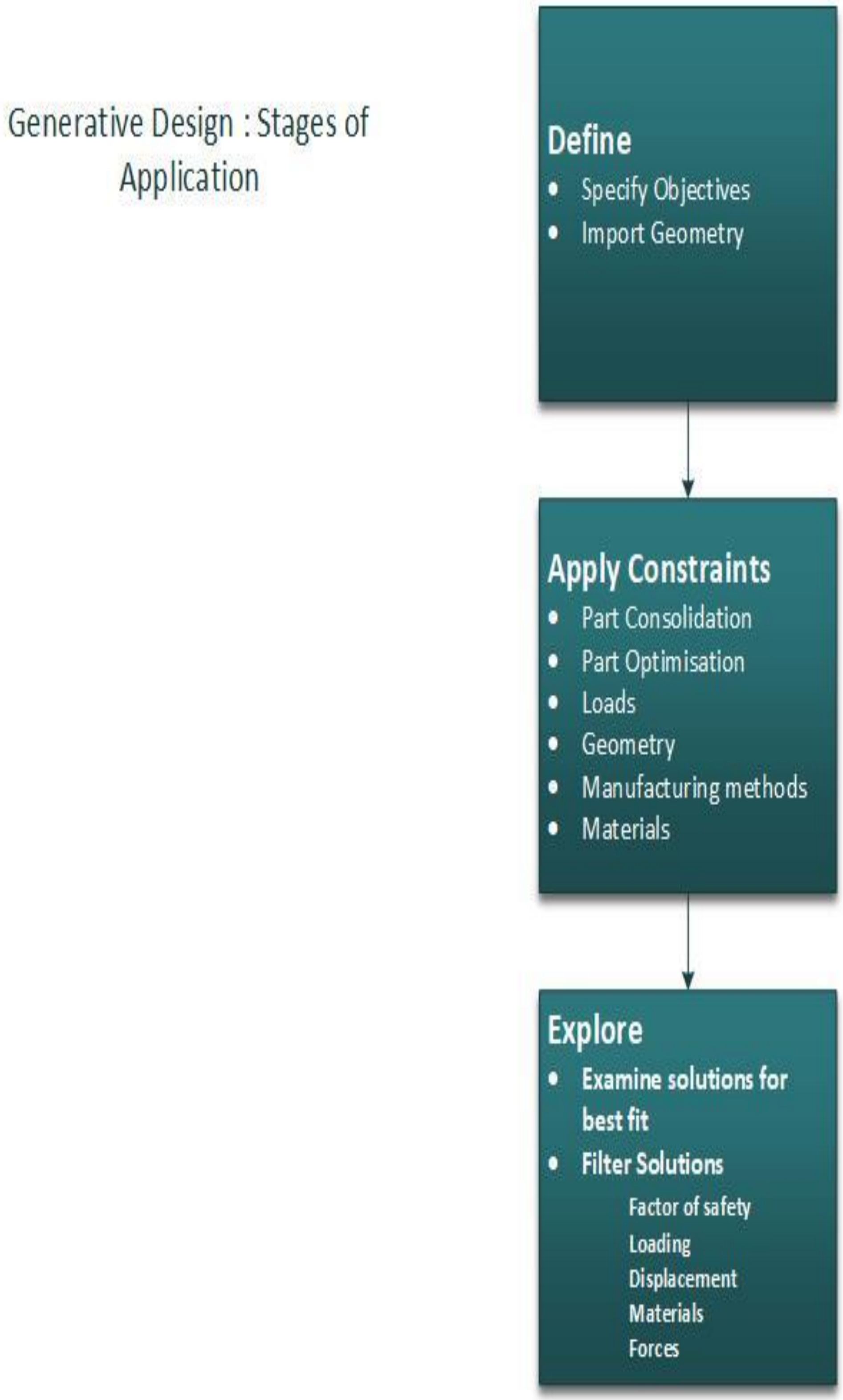


Fig. 39 Generative Design: Stages of Application (Fox.A,2019)

The power and speed of the AI cloud based generative design combined with the minimal setup requirements and the 3D fabrication flexibility of Additive Manufacturing can be leveraged to take advantage of:

- Reduced materials quantities
    - Resource conservation
        - Materials selection
- 'Matrixing' to reduce the number of parts in a product
    - Part Consolidation
    - Load constraint design
- Exploration of alternative manufacturing strategies and methods
    - Tooling Optimisation
- Improve multiple and interrelated objectives & Constraints Simultaneously

Fig. 40 Fusion 360 Digital representation of surface finished Generative Chair Iteration ,Fusion 360. (Fox.A,2021)

Autodesk Fusion 360 generative software platform is primarily a Computer Aided Manufacturing application, the ongoing development of which, has led to the incorporation of a Generative Design functionality. This application has a number of clear stages in which the solid model of a product can be entered into the Generative Design Environment and have parameters added to it which cover manufacturing methods, range of materials to be considered, loading, design requirements (material reduction, structural aspects etc.) It is possible to do simple preview assessments of the potential outcomes on a PC workstation, but full processing of all iterations and constraints requires a significant amount of computing power and may take some considerable time to process.

Once the environment is established the software creates numerous iterations of possible designs that best fit the aims and constraints. These can then be assessed by the 'Human Designer' through comparative functionality embedded in the software.

Below is a very basic example of a chair frame using simple solid modelling geometry to form the structure. The arrows on the model indicate the forces that the chair frame will be subjected to. These forces can be many and varied to represent the actual mix of forces anticipated to impact the structure. The panels on the chair back (elipse) and on the Seat platform (circle) are areas of 'Preserve Geometry'. The ring-fencing of specific areas of geometry informs the software that no generative transformation should occur in these areas to maintain the original form of the model.

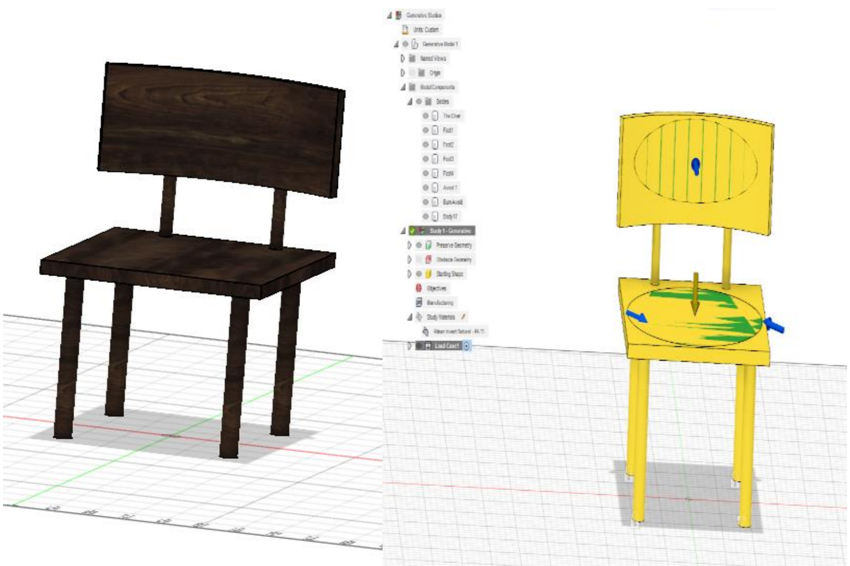


Fig. 41 Basic Chair Frame loading on Fusion 360 (Fox.A, 2019)

In addition to the 'Preserve Geometry', due to the freeform nature of the possible solutions, it may be necessary to add additional geometry to keep areas clear from material in the final solutions. This ring-fencing is known as 'Obstacle Geometry'.

These are particularly important in the formation of appropriate design solutions as the omission of these elements can render designs iterations unusable. The example iterations below were produced from the model without the use of 'obstacle geometry' it is clear to see that the solution has placed material around the chair legs in the form of a skin.

Fig.42 Iterations without 'Obstacle Geometry' identified (Fox.A,2019)

With Obstacle geometry identified and all other aims and constraints remaining the same the iterations below show that the iterations now respect the need to keep the area between the chair legs clear.

Fig. 43 Iterations produced with obstacle geometry identified (Fox.A,2019)

Below it can be seen that numerous forms are produced from a combination of the constraints and aims, the geometry produced can be significantly different in each case and it is then up to the Human designer to differentiate between these options to select the most suitable final solution for application or further development. On the Iteration example below, it should also be noted that the structure has a few organic additions to the main structure. For manufacturing and client appeal it is possible to clean and smooth these structures by post processing them using software such as Meshmixer. All designs produced through the generative process are ready to be post processed for Additive Manufacturing, 3 & 5 Axis CNC machining (The specification of the machining type has the potential to change the geometry of the iterations produced).

Fig. 44 An Example of another iteration from the same set of aims and constraints(Fox.A,2019)

In the example image produced through Fusion 360 Generative Design below, it should be noted, that when loads that are applied to the model interact & combine with other constraints the outcomes are not always symetrical.

Fig. 45 Outcomes from the iterative process may not always be symmetrical (Fox.A,2019)

Comparison of the iterations can be done manually from the perspective of aesthetic form and the more subjective and qualitative aspects of the designs; however, the quantitative data can be compared in a few ways using the tools available in the generative environment. Each iteration is displayed with its key characteristics ie. material used, manufacturing method, volume of material in the product, mass of the product, Von Mises stress factor and its factor of safety elements. The example below shows the layout of data in the Generative Environment.

Study 1 - Generative - Outcom...
Iteration 3 (final)

Properties

Status	Completed
Material	Rilsan Invent Natural - PA 11
Orientation	Z+
Manufacturing method	Additive
Volume (mm^3)	2.249e+7
Mass (kg)	22.943
Max displacement (mm)	9.19
Max von Mises stress (MPa)	5.2
Factor of safety limit	2
Min factor of safety	8.23

Fig. 46 Generative iteration analysis example Fusion 360 (Fox.A,2019)

Comparison can be made in this form by comparing all the iterations in one display as can be seen in the example below, but this may become difficult if the number of iterations is large.

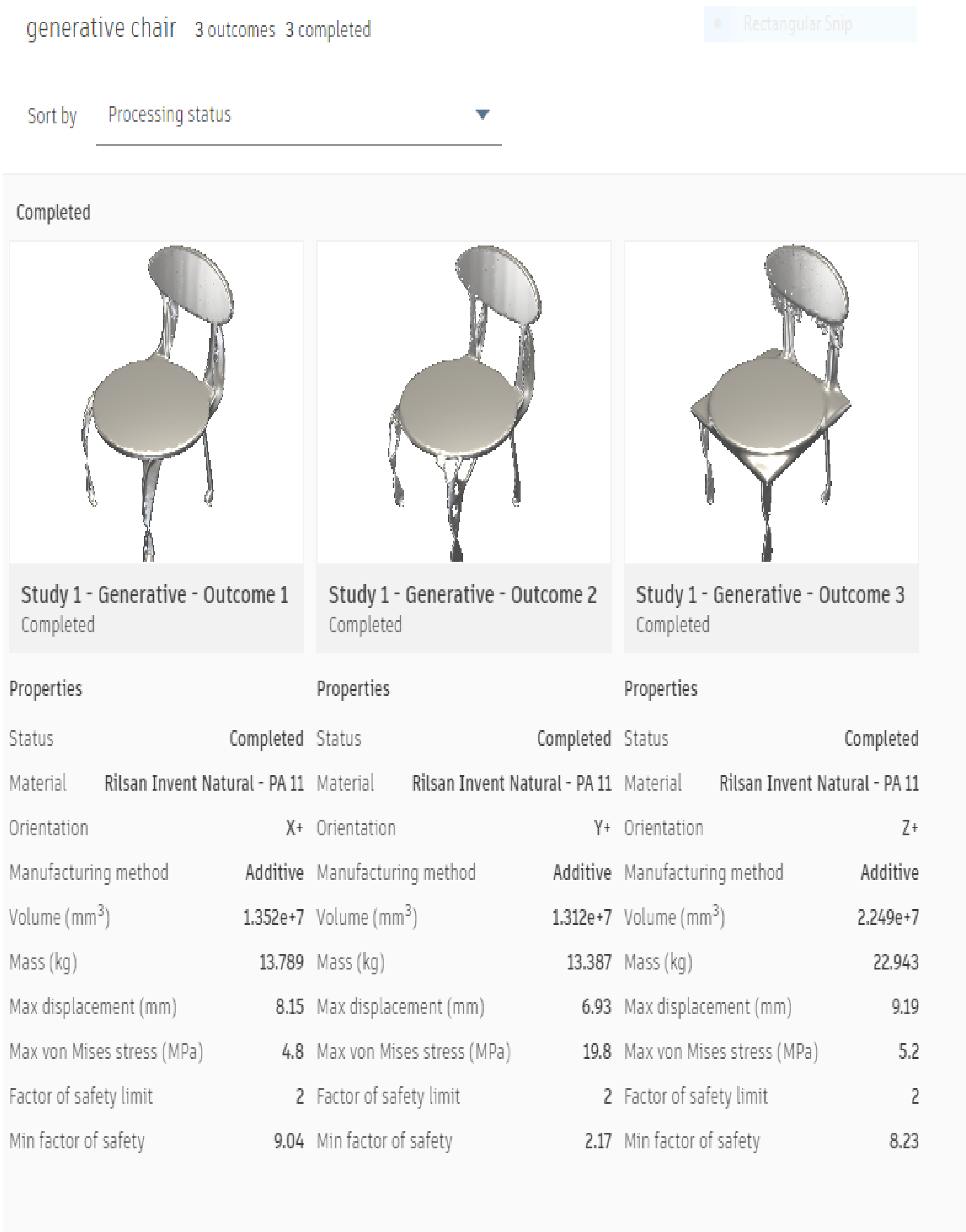


Fig. 47 Comparison of multiple generative iterations, Fusion 360 (Fox.A,2019)

When large numbers of iterations are produced it is far easier to assess the various characteristics using a graphical format.

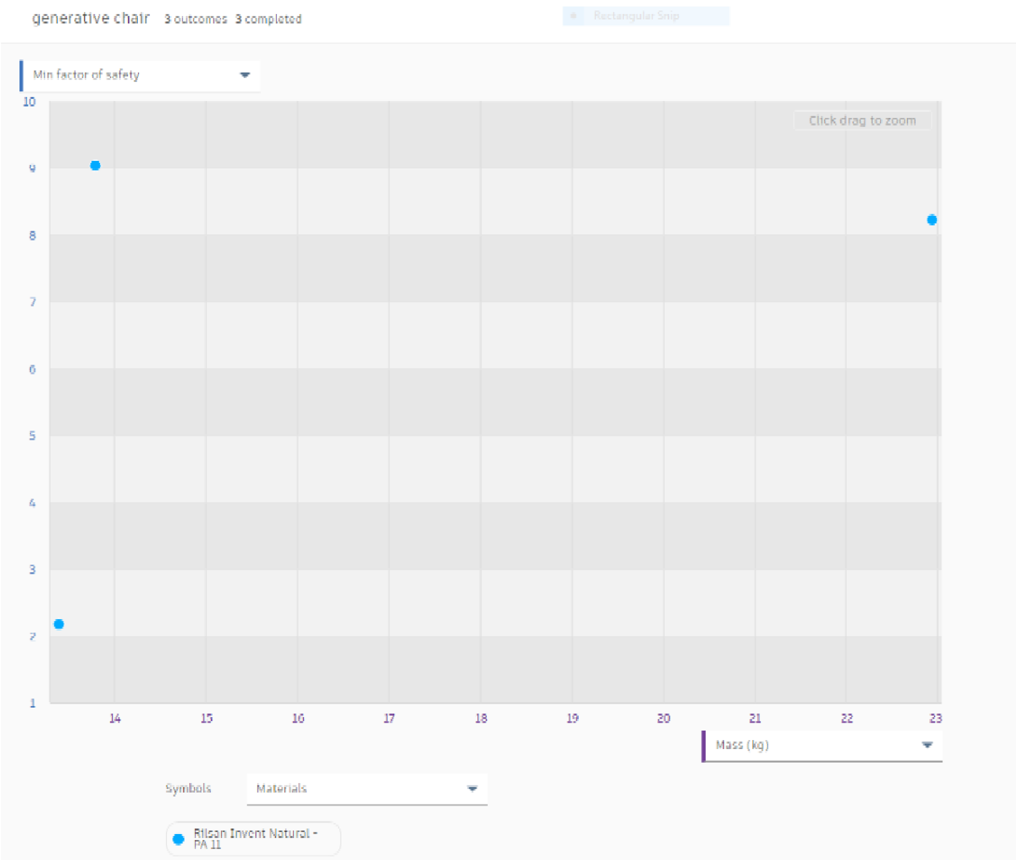


Fig. 48 Graphical display format to help explore the iterations generated (mass vs safety factor) (Fox.A, 2019)

The graphical comparisions can illustrate most of the key characterists shown in the table summary format but displays all the iterations relatively and the graph to assist in selection. The symbols can also be specified into processing status , materials and manufacturing methods in order to illustrate groupings in the outputs. A matrix of camparisons can be made using the following criterion:

- Mass
  (The quantity of matter in a body regardless of its volume or of any forces acting on it.)
- Max von Mises stress
  (Von Mises Stress was first proposed by Maksymilian Huber in 1904. This point (or stress) at which the material behavior transforms from elastic to plastic behavior is known as "yield stress". We often say that the material yields if the stress is greater than the yield strength.)

- Minimum Factor of Safety

  (The design factor is defined for an application and is not an actual calculation, the safety factor is a ratio of maximum strength to intended load for the actual item that was designed.)
- Maximum displacement

  (The maximum displacement or distance moved by a point on a vibrating body or wave measured from its equilibrium position)

On completion of the iterations and the selection of designs to be manufactured the generative models can be output as meshes or solid models to attach the machining strategies to them.

4.4 Initial full study using the 'Evolution Chair '

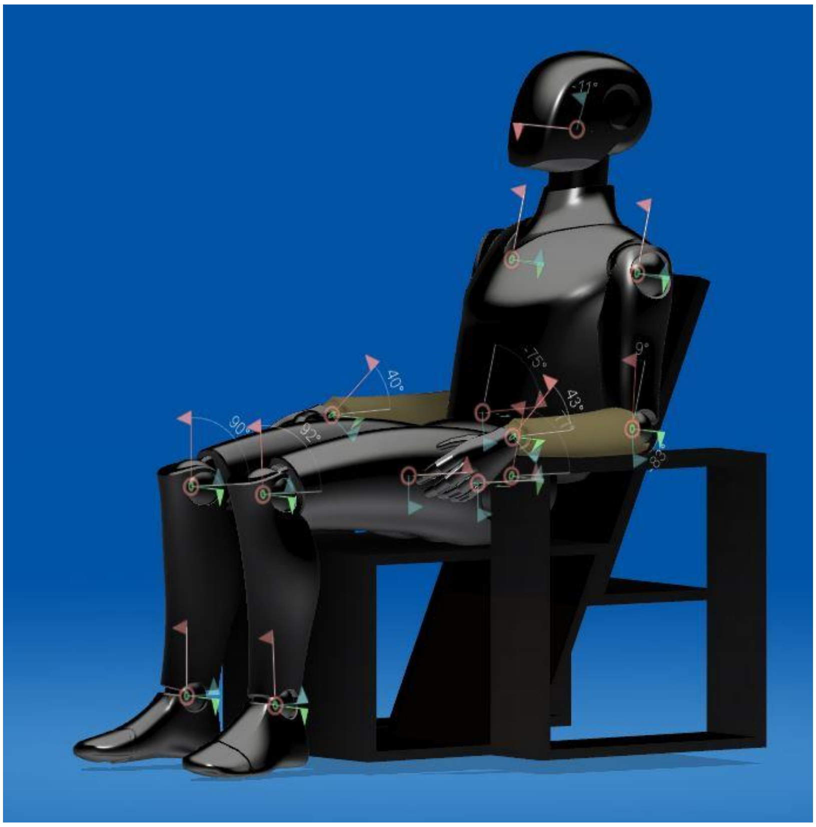


Fig.49 Digital Manikin used to develop design geometry and positioning (Fox.A,2019)

In order to achieve appropriate geometry and scale a virtual human model was used to ensure that the structure was sound from an ergonomic perspective. The model is fully adjustable on all joints and can therefore be manipulated into any pose that is required for the final design.

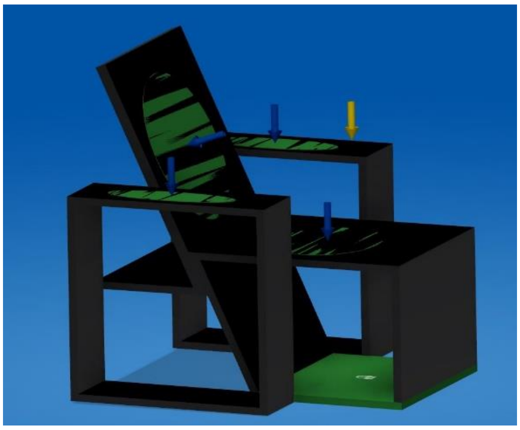


Fig. 50 'Preserve' regions & geometries established (Fox.A,2019)

Preserve regions or geometry (highlighted in green) conserve the geometry in its original form during the iterative process of optimising the designs in line with the constraints, objectives and manufacturing selections specified. These geometries can be elements of existing designs or can be geometry created to identify areas of loading.

If using existing design geometry one can identify elements as a starting geometry. In this way the geometry will be highlighted in yellow and will be identified as a body from which the iterative process will start its processing. Therefore, further constraining the design corresponds more closely to your original design geometry.

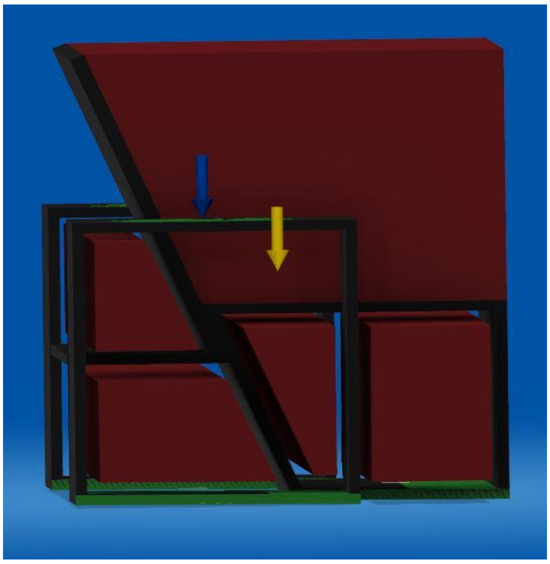


Fig. 51 'Obstacle' Geometry created and identified (Fox.A,2019)

Obstacle geometry (highlighted in red) can be created as additional elements in 3D space which restrict the formation of product geometries in spaces which have to be kept clear for access or other reasons. The positioning and the proximity of these bodies can have a significant effect on form and structure of the resultant design iterations.

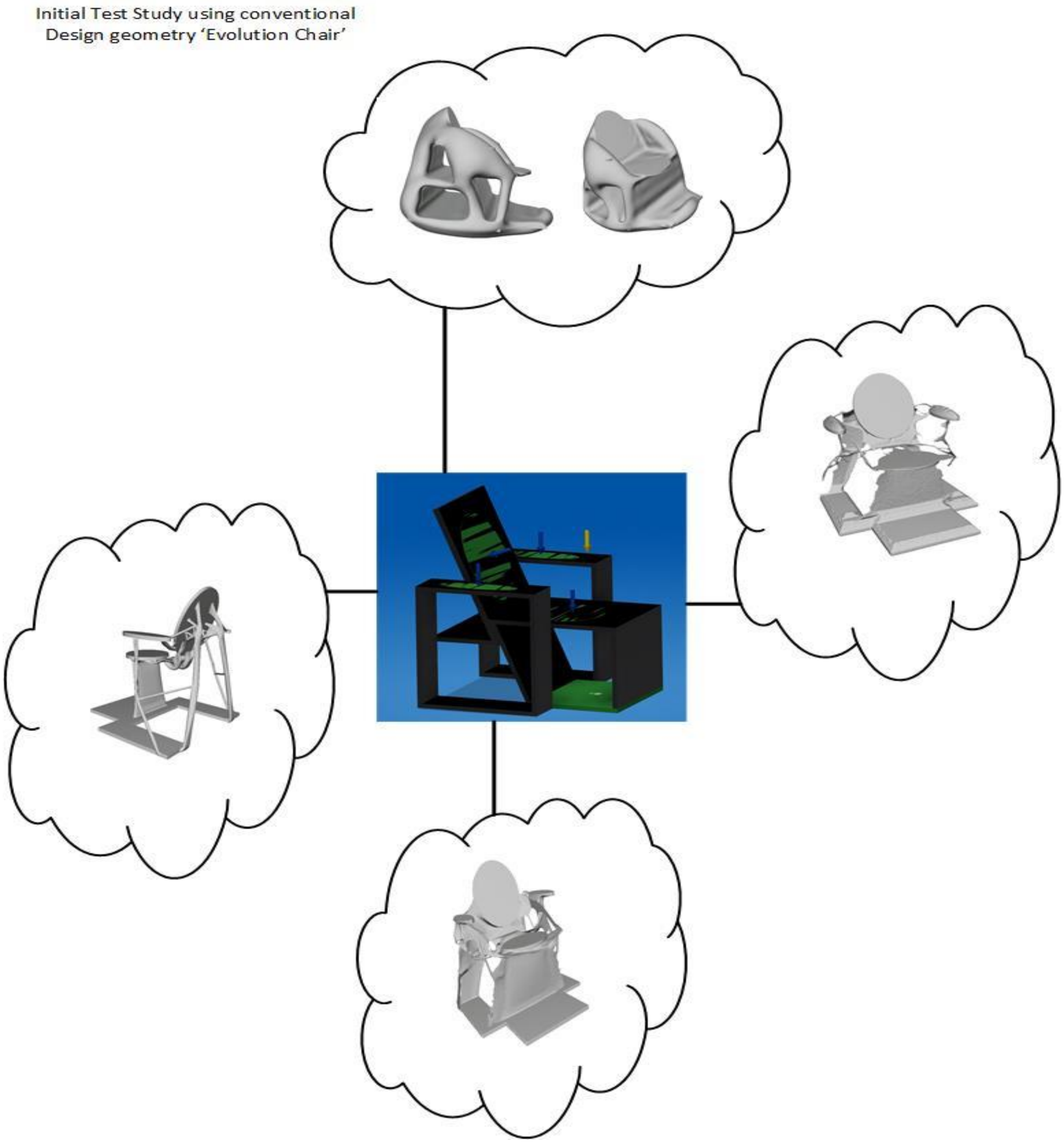


Fig. 52 'Evolution' Iterations produced (Fox.A, 2019)

4.5 Freeform AI based design.

The subsequent tests are based on loading areas without the remaining structural geometry of the furniture piece. In this way the software is less constrained by an existing structure. The iterations are controlled almost entirely by the obstacle geometry created by the designer when setting up the generative study environment.

In the image below with the 'manikin' made transparent one can observe the preserve areas to which loadings, pressure, moments etc. can be applied.

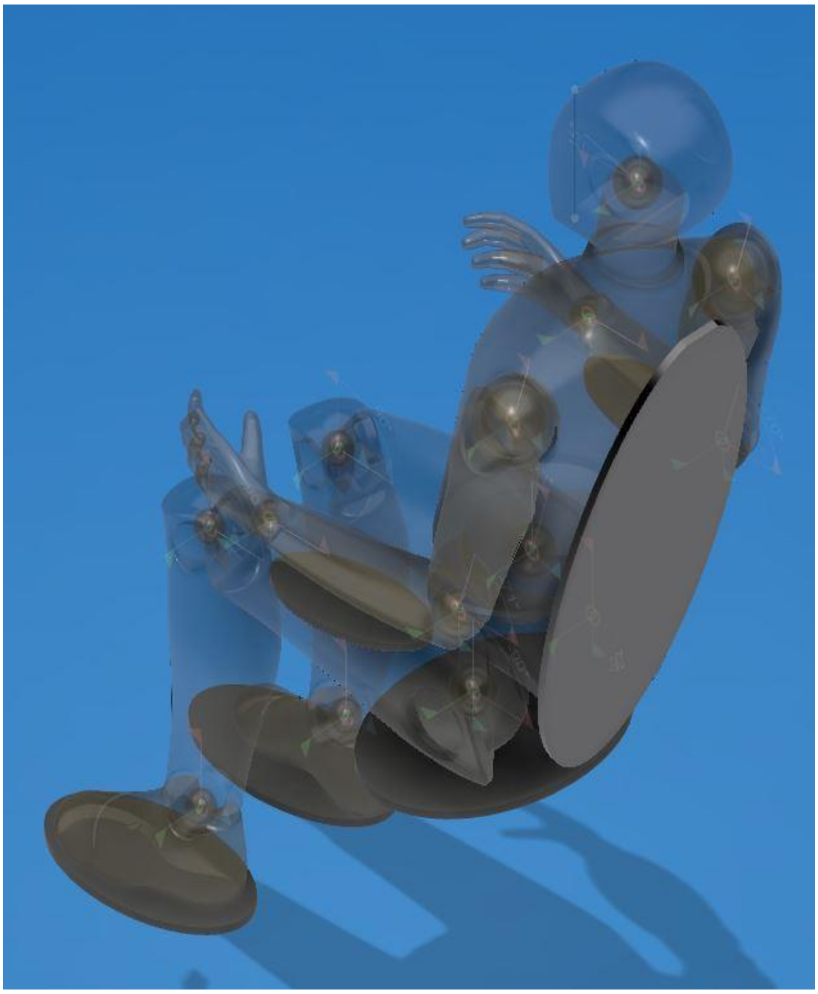


Fig. 53 Distinct & discrete areas on which generative rules are to be applied (Fox.A,2019)

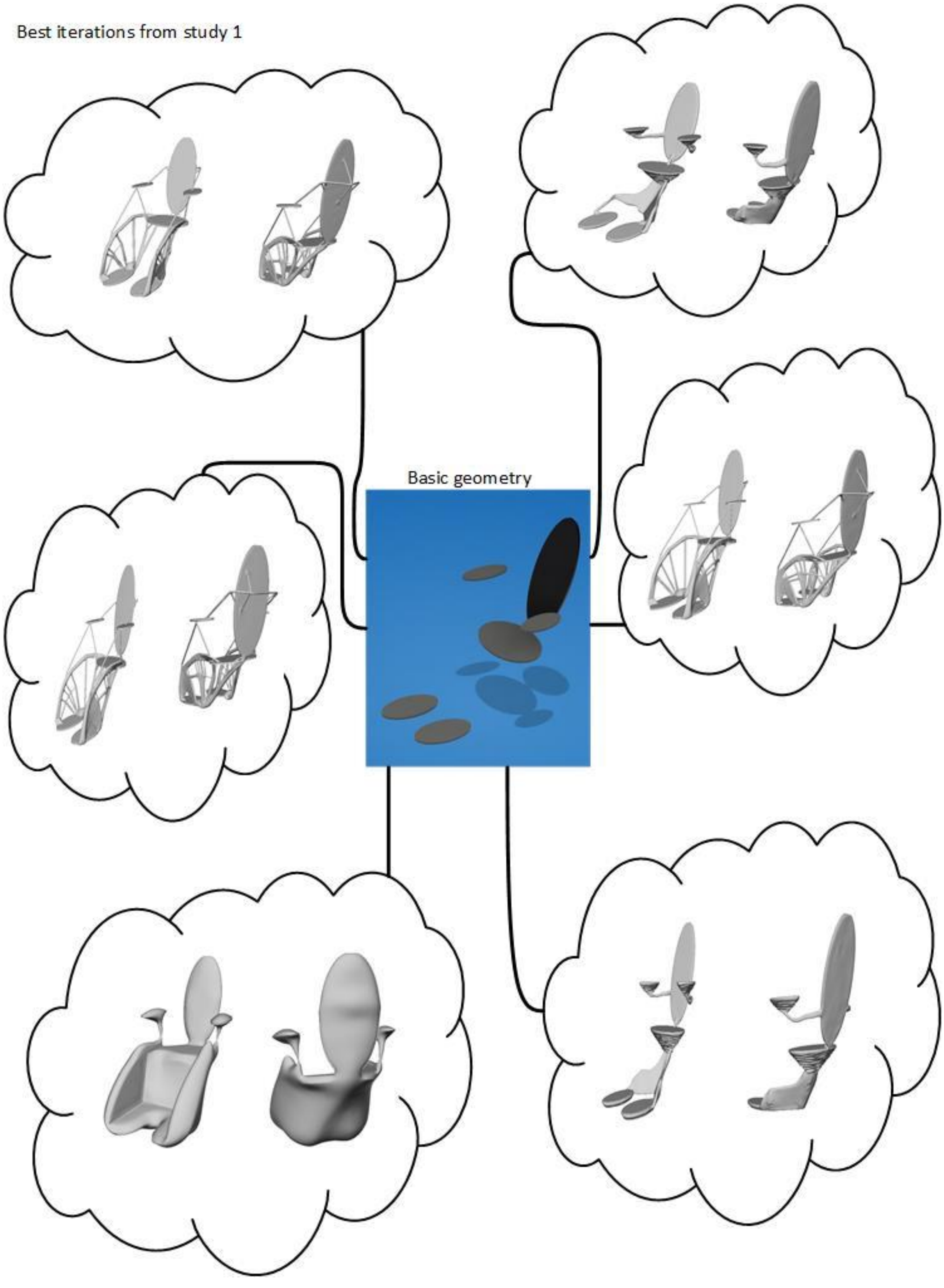
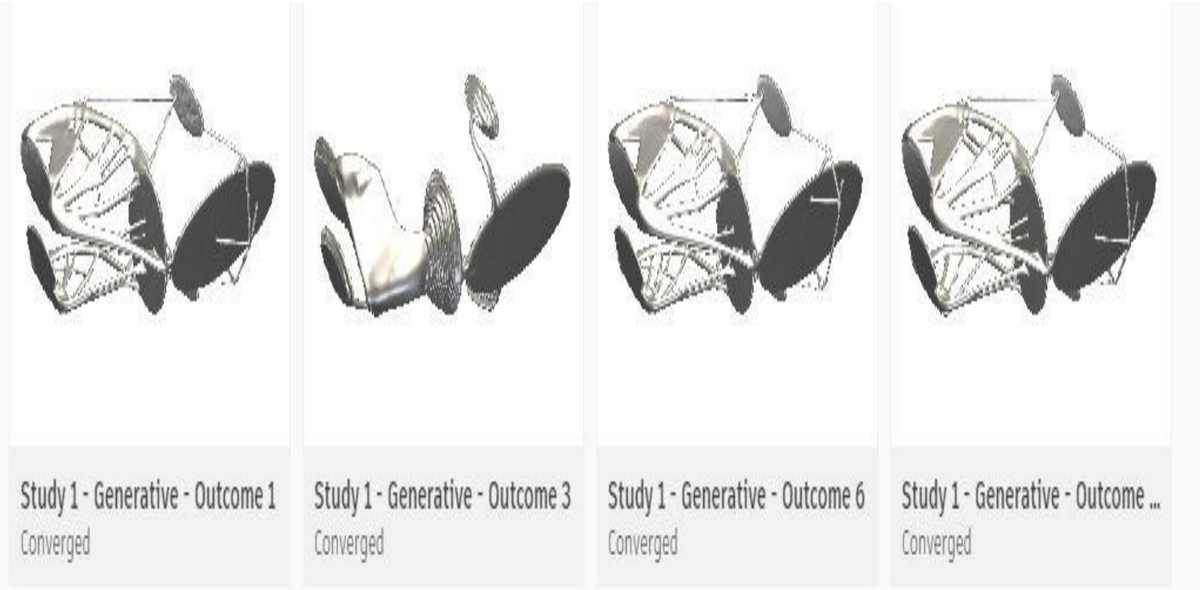


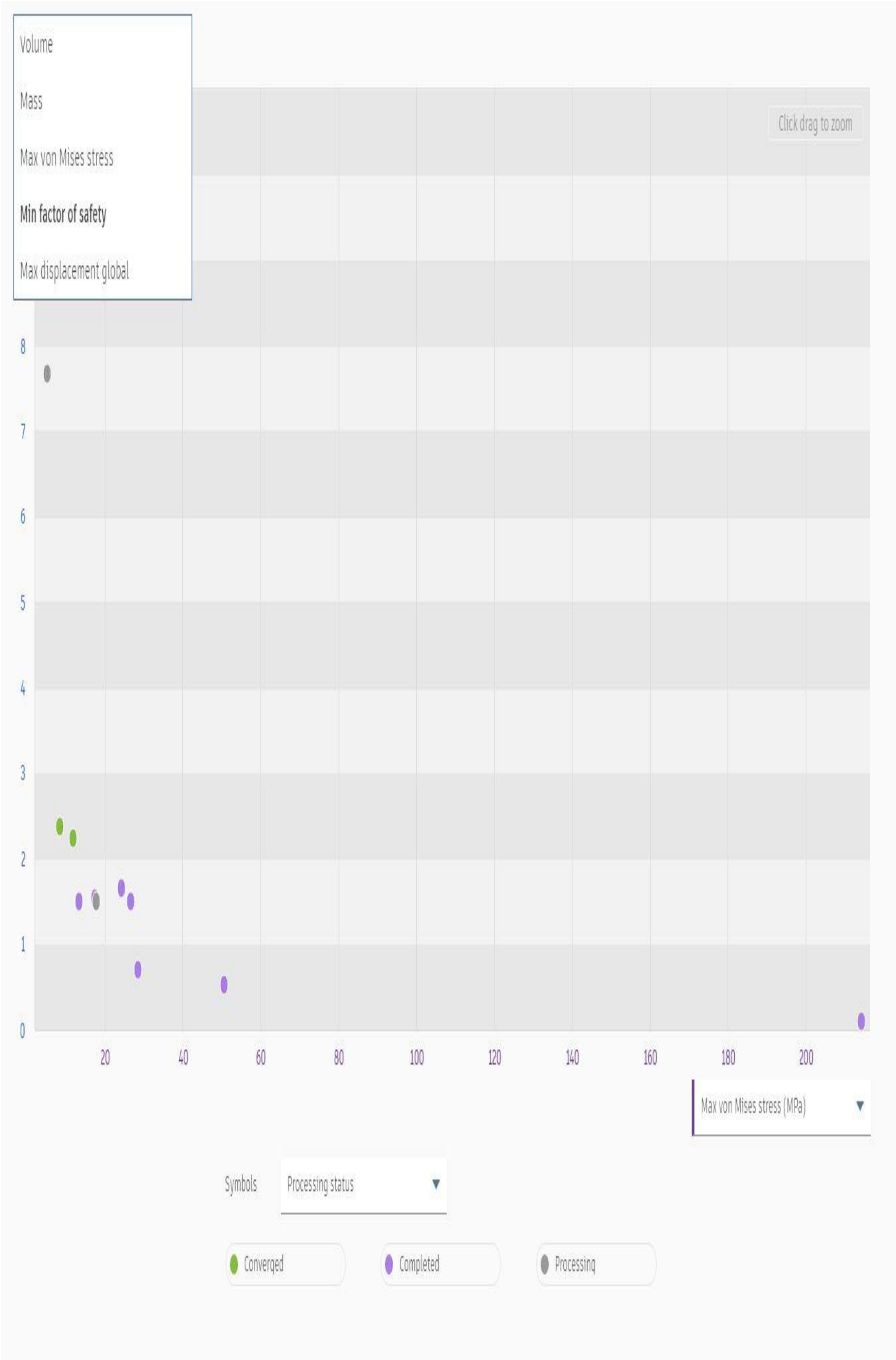
Fig. 54 Best iterations produced from the virtual generative study (Fox.A,2019)



Properties	Outcome 1	Outcome 3	Outcome 6	Outcome ...
Status	Converged	Converged	Converged	Converged
Material	ABS Plastic	ABS Plastic	Acrylic, Clear	Polystyrene, High Impact
Orientation	-	Y+	-	-
Manufacturing method	Unrestricted	Additive	Unrestricted	Unrestricted
Volume (mm^3)	7.819e+6	1.388e+7	7.814e+6	7.797e+6
Mass (kg)	8.288	14.714	9.299	7.968
Max von Mises stress (MPa)	8.4	13.3	4.1	11.8
Factor of safety limit	1.5	1.5	1.5	1.5
Min factor of safety	2.37	1.5	9.79	2.24
Max displacement global (mm)	5.46	59.32	4.64	6.75

Fig.55 Numerical comparison of these generative iterations (Fox.A,2019)

From the iterations processed on the cloud the outcomes are compared using interactive graphics which can be manipulated to illustrate the characteristics that are priorities for your design solution. In this way the human designer can critically examine the outputs and select those that are most suitable for further development and prototype manufacture.


Volume
Mass
Max von Mises stress
Min factor of safety
Max displacement global
Click drag to zoom
8
7
6
5
4
3
2
1
0
20
40
60
80
100
120
140
160
180
200
Max von Mises stress (MPa)
Symbols
Processing status
Converged
Completed
Processing

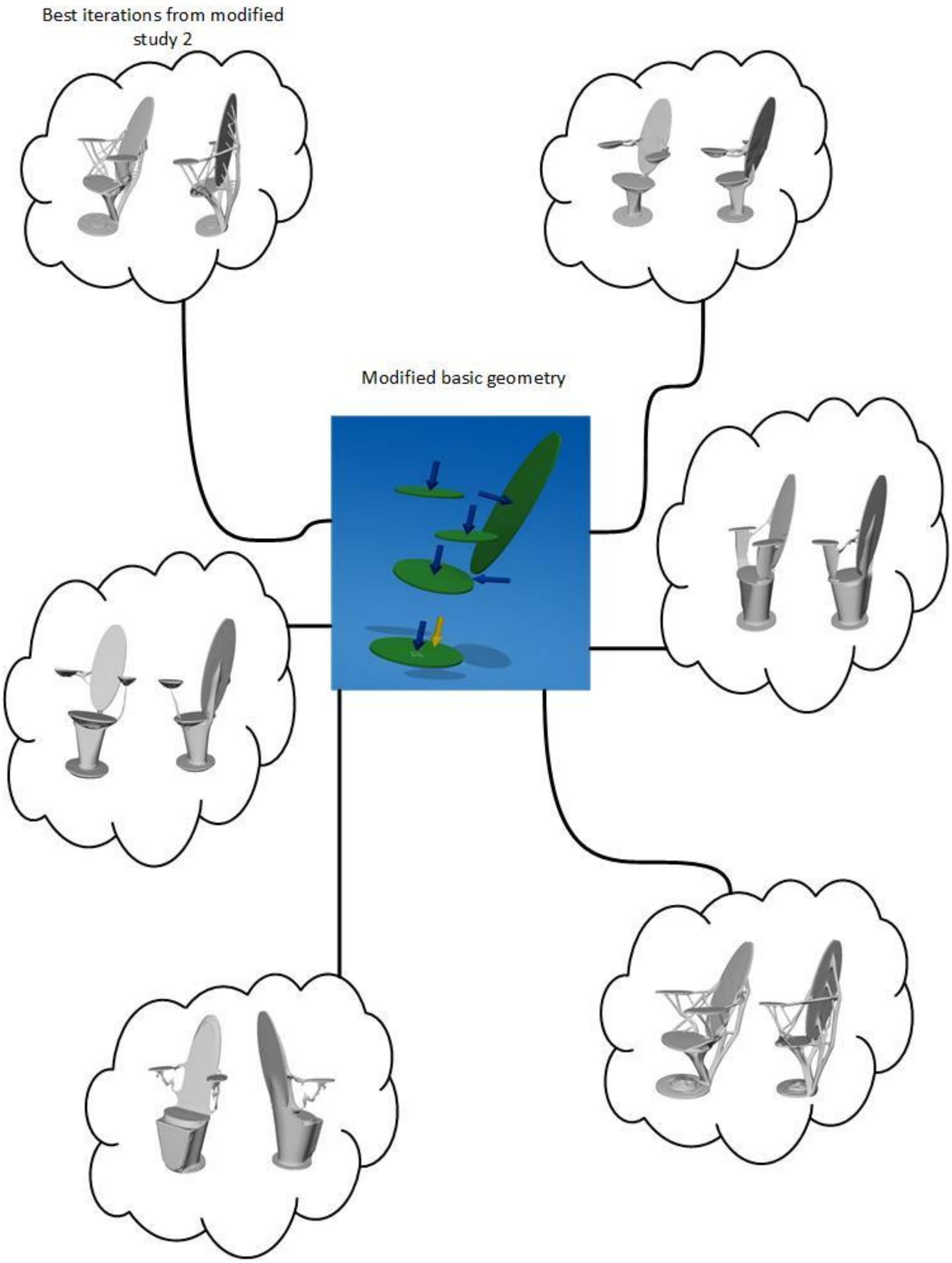


Fig. 56 Subsequent iterations produced from a modified generative study using modified geometry (Fox.A,2019)

4.6 Structural Testing

Assessment of the resultant iterations

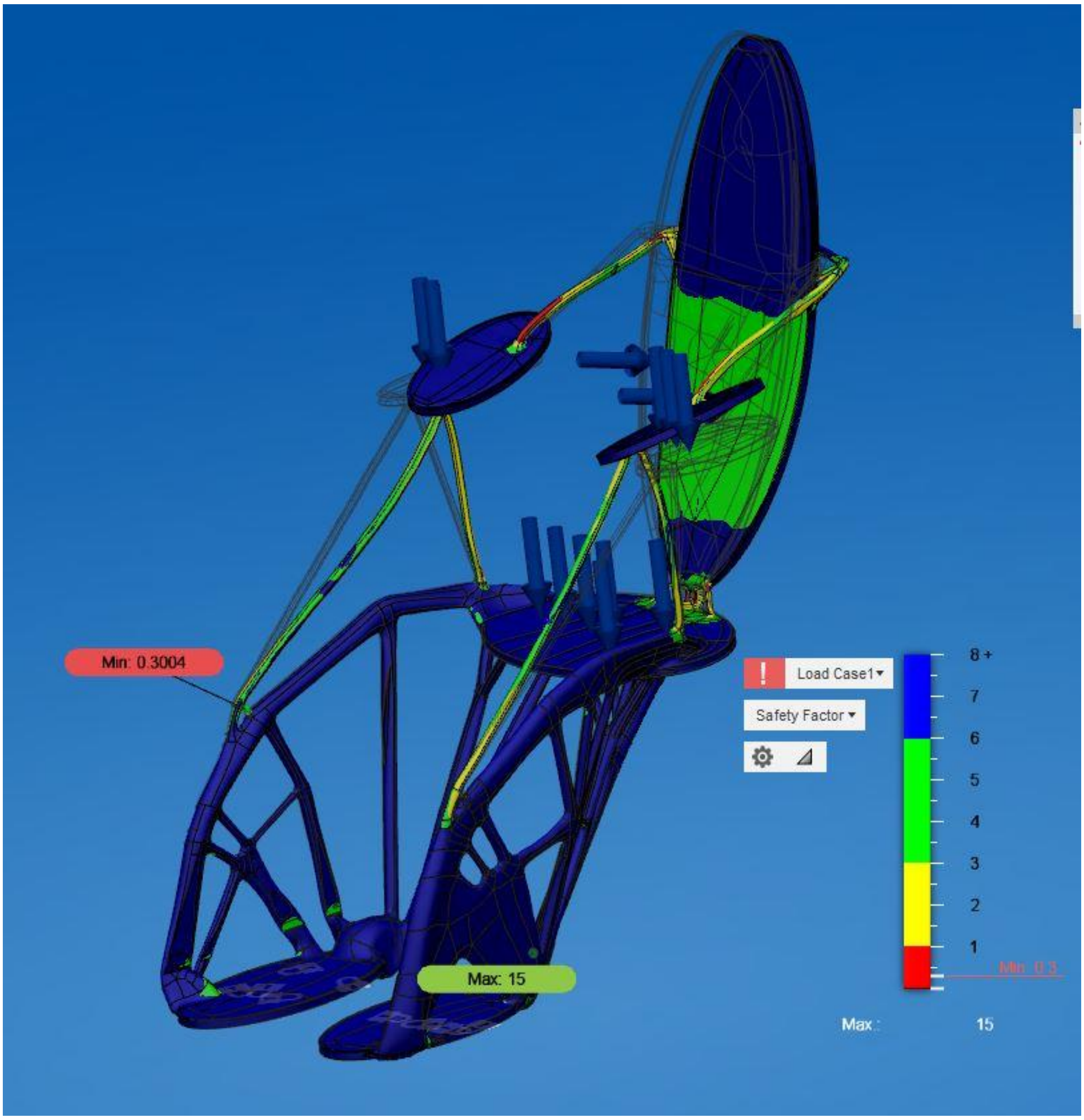


Fig. 57 Static Loading of the model (Fox.A,2019)

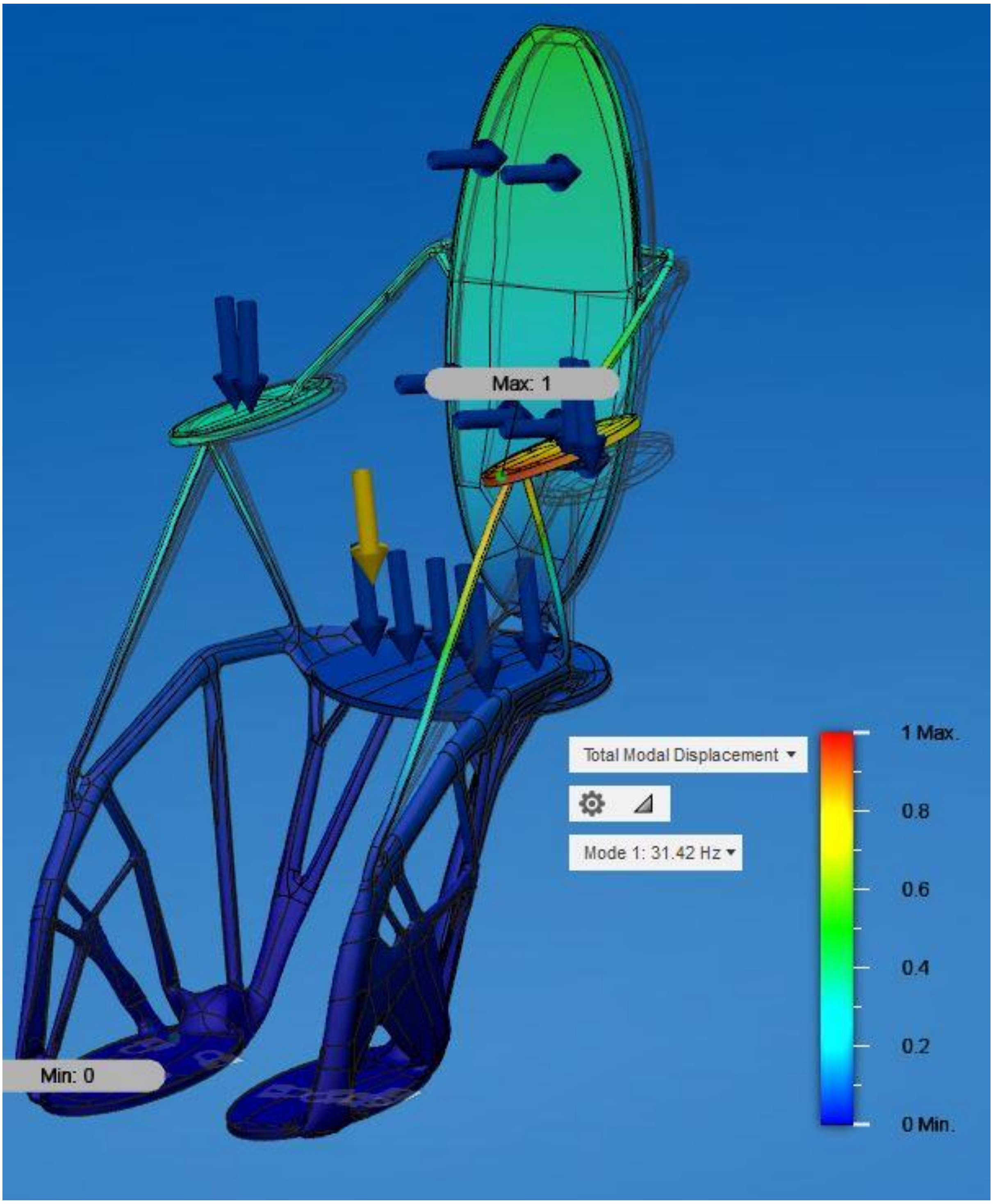


Fig. 58 Modal loading of the structures over a number of cycles (Fox.A,2019)

4.7 Design Symmetry

One drawback of current constraints is that they do not afford the designer the ability to create a symmetrical design iteration. It can be seen in the following image below of the iterations produced for the daybed geometry. It is obvious that the design is very different from left to right. This may not be an issue in many individual limited run artistic furniture applications, However, in the commercial furniture industry within the UK where standards and specifications need to be more exacting, the need for a symmetrical and balanced aesthetic outcome is important.

Fig. 59 Asymmetrical original iteration (Fox.A,2019)

These issues can be addressed by ensuring that forces plied to the structures are balanced as appropriate. This minimises local distortions throughout the iterations produced. If the resultant iteration still requires modification this can be done quite easily by applying the following actions to the original outcome.

Firstly, from a furniture designers' perspective one should examine the output and decide the important features that need to be retained and also those that need to be eliminated from the asymmetrical design. Once this is established a strategy can be developed to split the model and transform the remaining elements to create a symmetrical solution. In this example the solid model is being split using a plane running midway through the model.

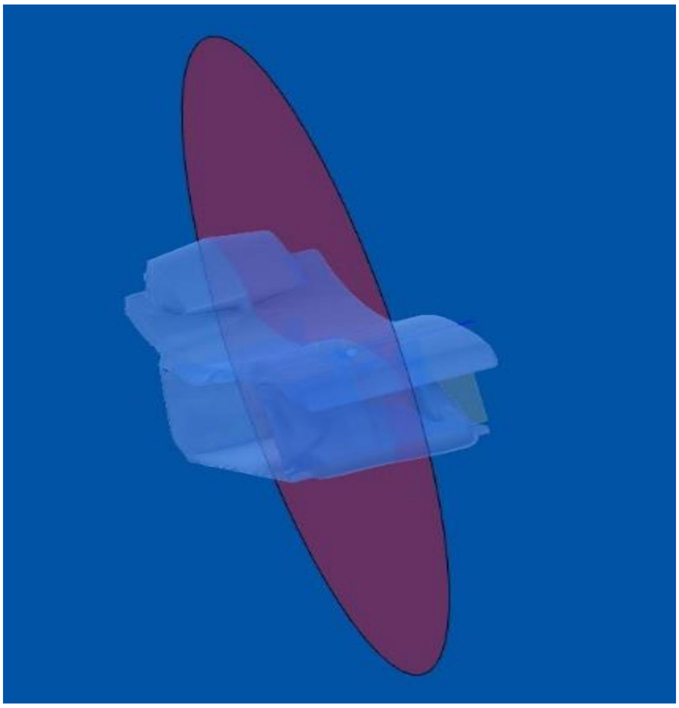


Fig. 60 Model split using center plane (Fox.A,2019)

In the following image it can be seen that the model is now in two distinct bodies. This is also reflected in the design history. When selected the two halves of the model are highlighted as two separate bodies.

Fig. 61 Model is now split into two bodies (Fox.A,2019)

Following the creation of the two bodies in this example the left hand body can be deleted. This action is again reflected in the design history and the bodies listed.

Fig. 62 Left hand body deleted (Fox.A,2019)

Once again using the same plane as the deletion one can then mirror the remaining body through it to create a symmetrical design for further testing and analysis. It should however be noted that at this point the model is still two separate bodies. Before any FMEA analysis takes place the two bodies should be combined to form a single entity. The two bodies in the design history will be replaced with one single body.

4

Fig. 63 When selected whole body is highlighted as one (Fox.A,2019)

Fig. 64 Reconfigured symmetrical design (Fox.A,2019)

4.8 KUKA Additive Manufacturing Robot Platform equipment, integration & programming

The KUKA KR6 700 the foundation of the physical robot additive manufacturing cell is a light payload robot arm with a capacity of max 6 kg decreasing to 3kg at full extension. The reach of this robot is 900mm and has a work volume of approx. 1.3 cu meters.

KR AGILUS-2 KR 6 R700-2

Max. reach 726 mm

Rated payload 6 kg

Pose repeatability ±0.01 mm

Number of axes 6

Controller KR C4 compact

KR C4 smallsize-2 Teach pendant KUKA smartPAD

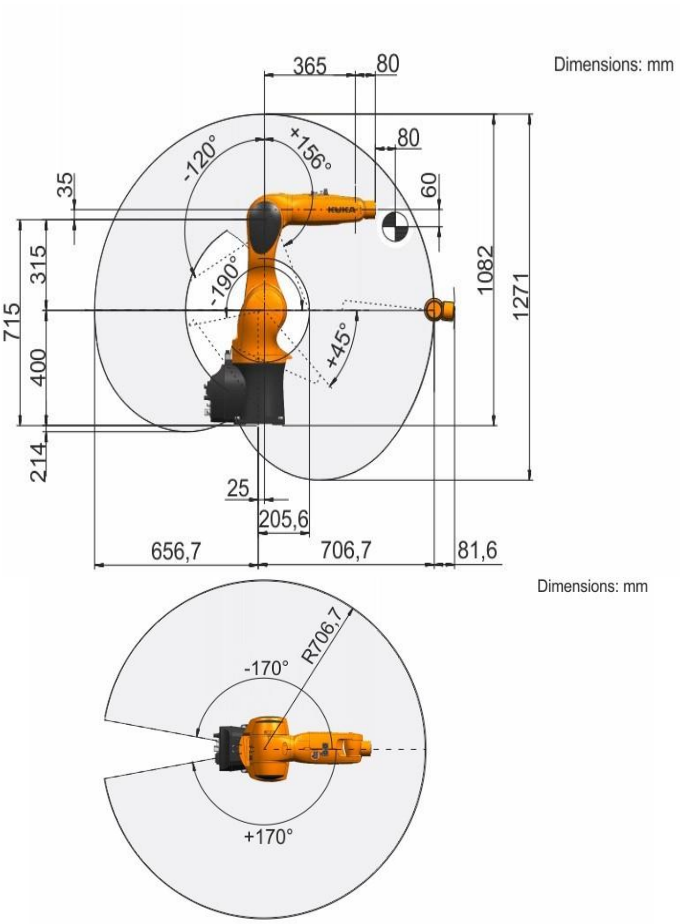


Fig. 65 KUKA KR6 working envelope

The Kuka Robot interfaces are as follows:

The interface is located at the rear of the base frame.

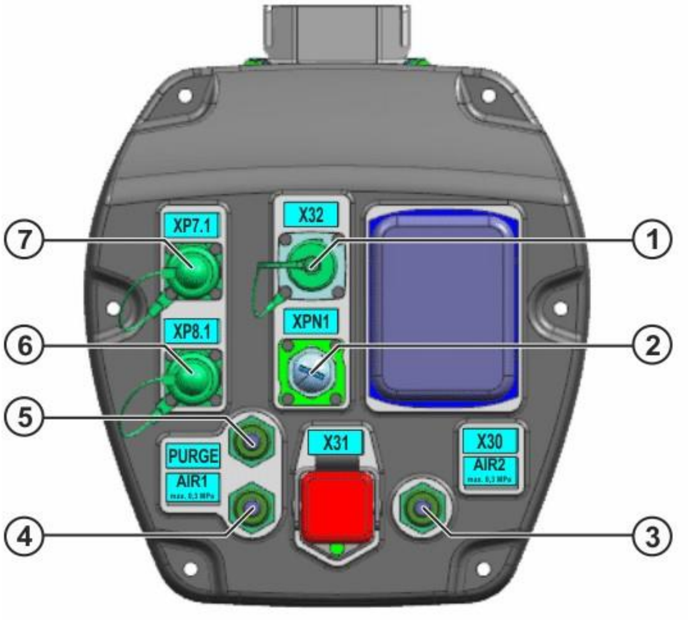


Fig. 66 KUKA KR6 Interfaces

Client interface

1 MEMD connection X32

2 CAT5 data cable connection XPN1

3 Airline connection AIR2

Outside diameter: 6 mm

4 Airline connection AIR1

Outside diameter: 6 mm

5 Pressurization connection (optional)

Max. pressure: 0.3 bar
Air, oil-free, dry, filtered

6 Connection for external axis A8 (XP8.1)

7 Connection for external axis A7 (XP7.1)

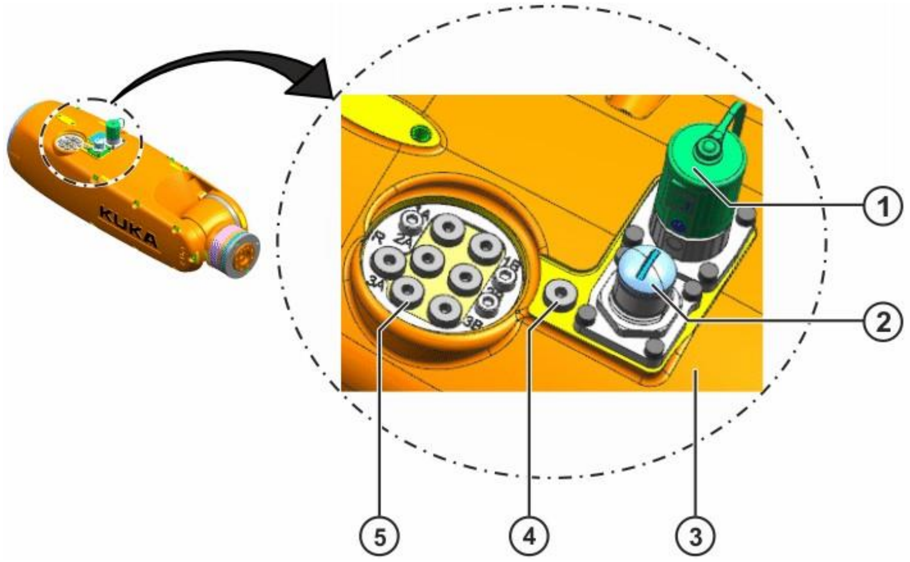


Fig. 67 KUKA KR6 Robot arm mounted interfaces

1	Connection X414	4	Airline AIR2
2	Connection XPN41	5	Air connections
3	In-line wrist		

In some industries the issue of accuracy may well be a primary concern regarding its implementation. CNC machines still have the edge over robots in this particular area. However, in the furniture manufacturing industry these requirements are far less stringent. The requirement for Additive Manufacturing is in the region of 0.2 mm which is well within the scope of most industrial robots e.g., the KUKA KR6 now has a repeatability of 0.01 mm. Robot machining, both subtractive and additive is positioned to take over from conventional CNC machine tools in many areas of manufacturing.

CNC automation in its traditional form tends to have very a large footprint but their actual working space is small as a ratio. Industrial robots however have a very large workspace in comparison to their footprint with the average medium sized robot having in the region of 7 -8 cubic meters of workable space. This can also be upgraded using the same robot with the addition of an additional axis.

The major strength of Robots is their flexibility being able to be moved from one task to another almost seamlessly. Most CNC machines are limited to 3 or 4 degrees of freedom with five axis machines being the ultimate. Industrial machining robots are almost all 6 degrees of freedom which will allow for the machining/printing of almost any shape that is required.

Rigidity is an issue for high accuracy applications where hard materials are being processed. Robots on average have a stiffness of one newton per micrometer and a natural frequency of 10 Hz. Machine tools on the other hand have stiffness values in the region of more than 50 microns per micrometer and natural frequencies in the several hundreds of thousands.

Both categories of automation can be expensive, however robots have two distinct advantages over traditional CNC style machines:

- Large workspace
- Versatility

The possibility of machining/printing objects of practically any size, shape and complexity mean robots can offer more value to a business for less cost. It has been established that a robot is 30% more cost effective than a Machine Tool with the same workspace (University of Mons).

The interfacing of the robot and the extruder require a number of issues to be considered:

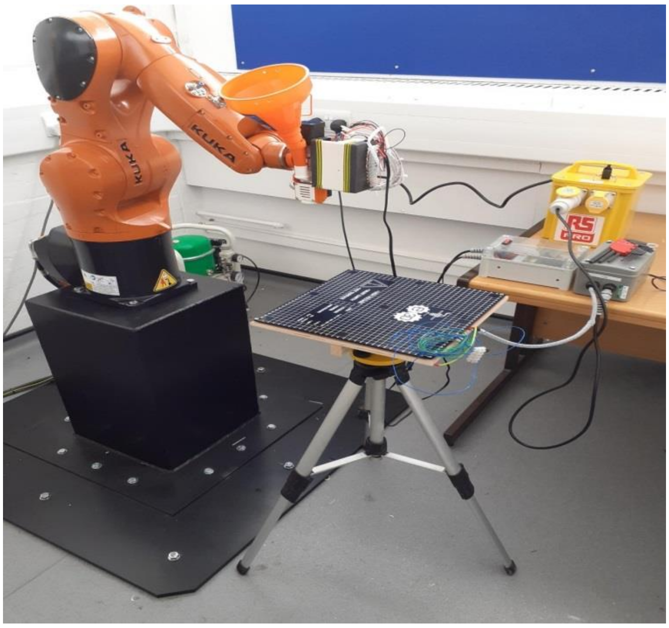


Fig. 68 Brunel KUKA Robot Additive Manufacturing Cell (Fox.A,2019)

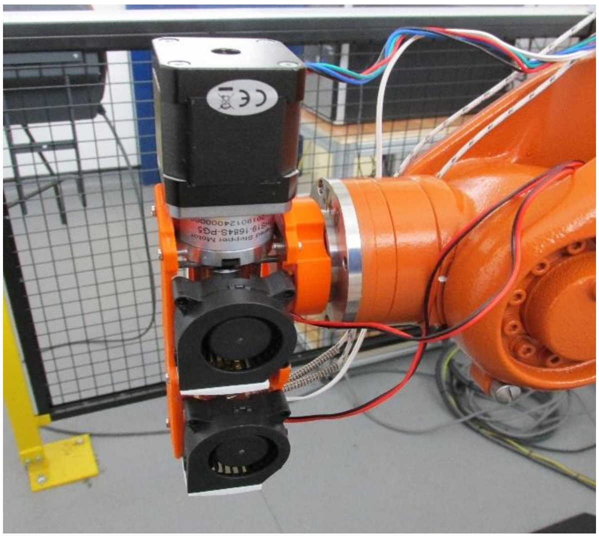


Fig. 69 Bespoke Mechanical interface designed and manufactured (Fox.A,2019)

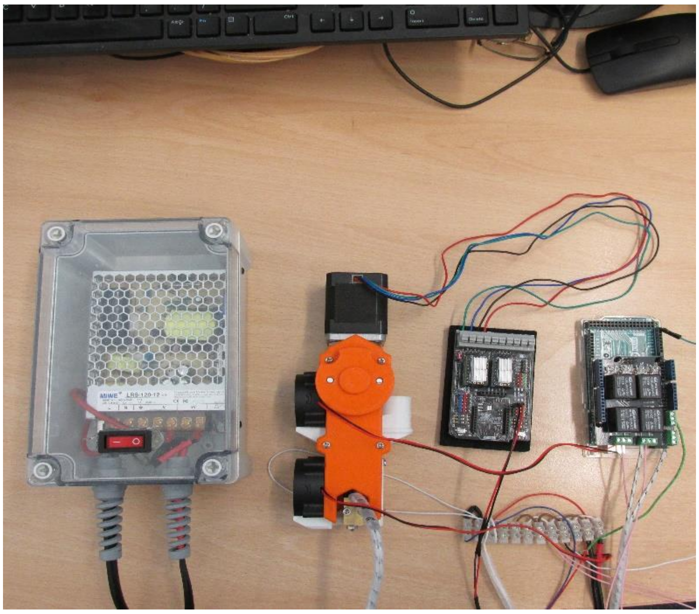


Fig. 70 Completed hardwired extruder control system (Fox.A,2019)

In order to successfully use the extruder in conjunction with the KUKA robot arm or indeed a conventional 3d printer it must be able to process materials from a number of media. The design of the extruder will enable it to be used with pellets, filament or strips obtained from recycled products. In the case of pellets it also allows for a certain degree of graded printing by altering the materials in the hopper during the print. Filament extrusion does however give a relatively tight deposition tolerance which is lost to a degree with direct pellet extrusion. To maintain the stability of pellet extrusion it may be necessary to keep the Extruder vertical and change the orientation of the part.

A direct feed screw extruder has been selected as the best solution to achieve accurate flowrates without the inherent problems associated with Bowden tube fed arrangements. The multi-media ability of the extruder will assist in the resolution of problems of printing with 6 degrees of freedom (DOF).

It is estimated that the extruder will weigh approx. 1 kg. It should have a supply hose diameter of approx. 20 mm to ensure the smooth flow of the pellets to the auger screw.

Extruder motor: 25-100 steps per unit

Stepper power will be approx: 1.7 A

Stepper reducer: 5:1

Heater: 12 volt 40w

Thermistor: 100k Negative Temperature Coefficient(NTC)

Hotend : M6 threaded nozzle

Capacity: 0.4mm – 2.0mm

Print speed: 30 – 60mm per second

Rapid travel speed: 100 – 120mm per second

The Integration process of the Kuka KR6 robot began at the very grassroots level, as this university robot had not been used for some considerable time and required, new system batteries, initial setup and re-calibration of the joints using the Kuka specialist tools which I undertook with the assistance of a Kuka Robots UK service engineer. In addition to this remedial work to bring the robot to a serviceable state, there was also at the time no real expertise in the department for the practical operation of the Kuka Robot which meant the first task was to arrange training for myself and some technical staff. Despite having many years' experience with CNC conventional subtractive machining and five axis operation, this was my first encounter with a Kuka Robot. The training therefore enabled a level of competency to be established in the basic robot operation via the Kuka KRC4 controller and the use of the Kuka SmartPAD pendant. The pendant allowed for the easy manipulation & Jogging of the Robot in World, Base and Tool co-ordinate spaces, together with the ability to execute, adjust programs and run initialization or Block Coincidence (BCO) procedures easily.

Having established this base competency, it was now necessary to interface RoboDK & Kuka PRC with the KRC4 robot controller. This took some time to achieve and with some further advice from both RoboDK and Kuka a middleware software application named KUKAVARPROXY.EXE was installed and the parameters entered into the KRC\R1\STEU\$config.dat file found in the c:\KRC\ROBOTER\KRC\ directory on the remote pc connected to the controller. When this program is run in the background it establishes the link by which data can be transferred between the RoboDK development environment to the KRC4 controller for subsequent actioning by the SmartPAD pendant.

Having now established a type of 'Digital Twin' on which the robot programs can be manipulated simulated and downloaded to the controller, my attention then turned to the creation of the Extruder to enable a robot-based extrusion print process. This took the form of a screw fed extruder which needed to be physically and electronically interfaced with the Robot. The extruder was fabricated, and customized physical interface components were designed on Solidworks and SLA printed in ABS to engage securely with the Kuka wrist coupling geometry and securing bolts. Following initial testing and assessment it was found necessary to stiffen them, this was easily achieved on the prototype by laminating the components with epoxy and small aluminum panels.

The ducting and fan couplings for the cooling of the printed material and the fins of the extruder body were also produced via Solidworks and Stereolithography (SLA) printing.

The Extruder hardware was then interfaced with the Arduino Mega 2560 control board which was linked to the Robot PC via a USB connection. This interface fed back information regarding the print state to the Robot control PC and the RoboDK application. The information monitored and fed back was focused on the Print head temperature and the temperature of the rapid heating 110v print platform. These elements are essential as the system must wait for the specified temperatures to be achieved before starting the printing process. It is particularly important as damage to the Extruder is possible if the print process begins prematurely, as the feed auger may be unable to turn in the low temperature solid or higher density polymer already in the chamber.

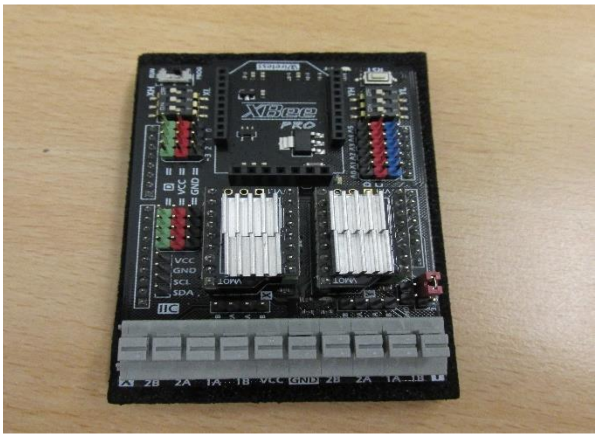


Fig. 71 Stepper motor Arduino shield DVR 8825 & Relays (Fox.A,2019)

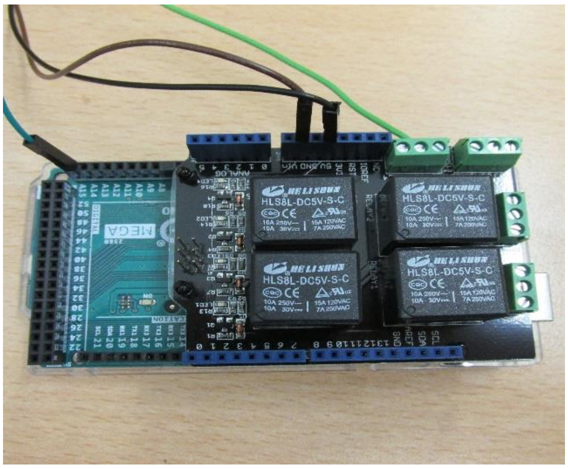


Fig. 72 Relay shield for Arduino , heater and fan control (Fox.A,2019)

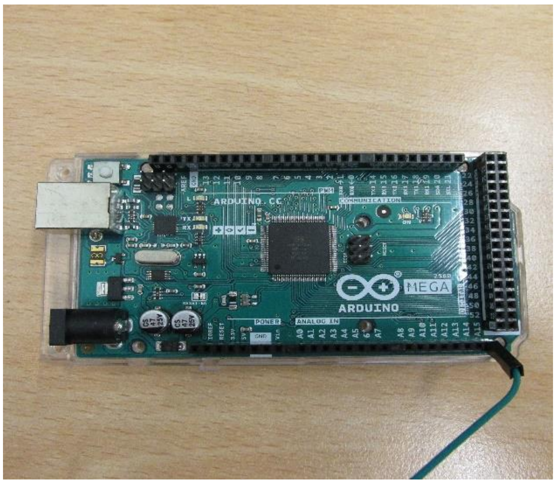


Fig. 73 Arduino Mega 2560 Control Board (Fox.A,2019)

The Arduino control system was specifically designed to run off a separate 12v power supply, while the heated build platform was run from its own separate 110v regulated power supply as this enabled one essential element to be minimized, that of initial setup time. This is a key element of the system flexibility and enabled the achievement of a fully heated platform to be achieved in around 40 seconds, as opposed to minutes for low voltage alternatives.

Fig. 74 240v/12v 10A power supply (Fox.A,2019)

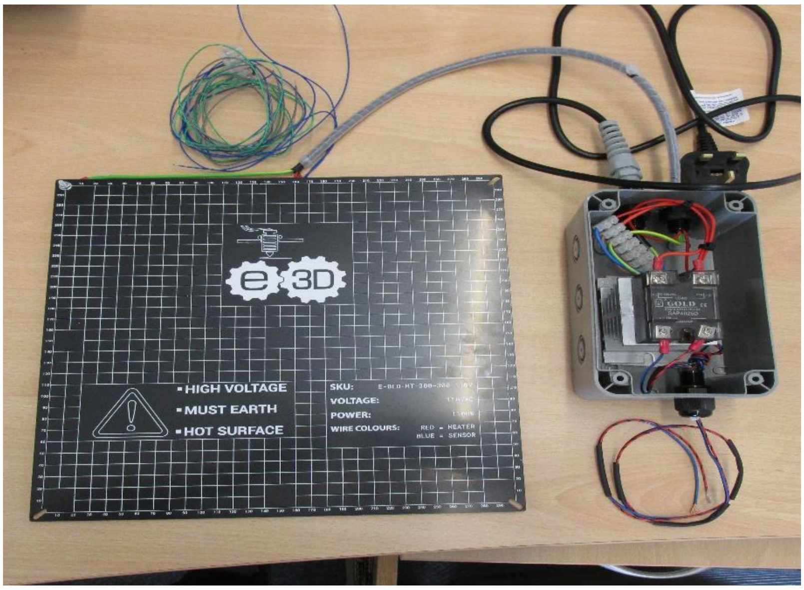


Fig. 75 Completed hardwired fast heat build platform (Fox.A,2019)

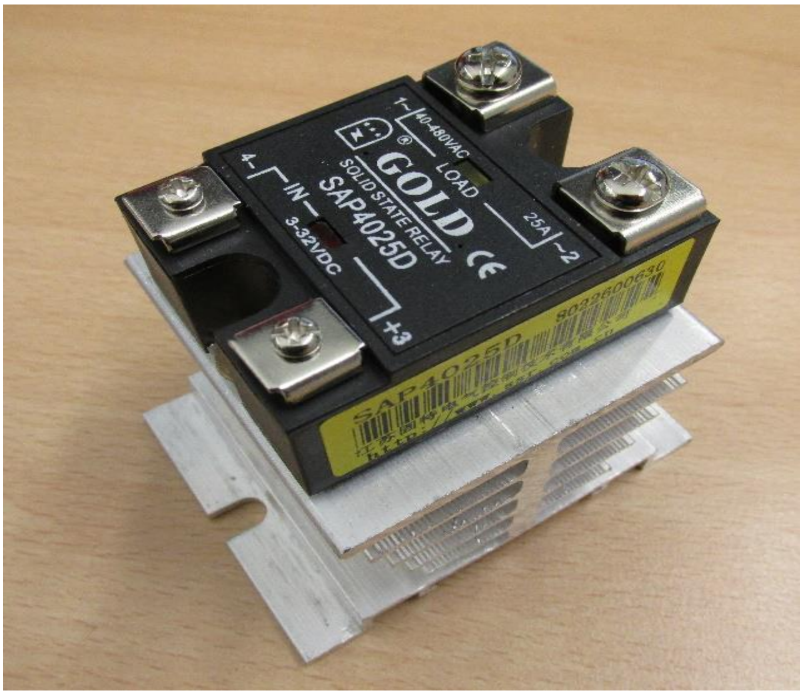


Fig. 76 Relay for 110v/5v heat bed control (Fox.A,2019)

Fig. 77 110v 1.1Kw fast heat build platform (Fox.A,2019)

Fig. 78 Regulated 110v power supply (Fox.A,2019)

All temperatures were fed back to the controller via thermistors located on the print head and placed under the heated build platform. This element needed initial calibration with an independent thermistor connected to a multimeter, to ensure the entered values actually represent accurately what was occurring physically on the hardware.

The very first attempts to print were not very consistent until the key parameters for the process were incrementally determined over a period of time leading to a far more reliable system able to deliver scaled model printing with an acceptable surface finish and robustness. These elements would obviously need quantifying more specifically if one were to print full sized furniture pieces as apposed scaled models on this integrated test platform. This detailed performance analysis was therefore considered to be outside the scope of the research until the platforms' potential expansion to a full-scale system in the future.

Following a number of initial tests and re-calibrations it was established that the system temperatures offering the best results were 180-200 Deg. C print head temperature and 60 Deg. C heated build platform temperature for Polylactic Acid (PLA), while a print head temperature of 230-260 Deg. C and a heated build platform temperature of 100-110 Deg. C was optimum for Acrylonitrile Butadiene Styrene (ABS).

Other issues which needed assessing and integrating into the control platforms were the flow rate in conjunction with the extruder diameter being used (i.e., The speed of the auger stepper motor and the diameter of the extruder (2mm), the speed of the print path

(200 mm per minute in testing) and the layer height (0.8 to 1.2mm in testing) of each sectional slice of the model produced by the Cura slicing application.

These variables change for each material type and need to be determined to action change in the surface quality of the prints produced. The layer heights of the print will also influence the layer adhesion and hence final strength of the products produced. There will however be tradeoffs between surface finish, strength and the time taken to print the object.

These specifications will depend exclusively on the product being printed, the materials being employed and the importance of surface finish and strength requirements for that specific application. Of course, these parameters would be significantly different on a full-scale printing operation using a customised full size commercial extrusion system.

The interfacing of the software modelled elements of the platform, seen in Fig. 79, proved to be relatively straightforward as all used a wide range of standard file formats for the transfer of 3D models to and from Solidworks, Fusion 360, Kuka PRC, Magix Design Studio and RobotDK etc. RoboDK also had a number of plugins which could be used directly in the modelling platforms for ease and increased integration.

The data from the solid model attributes and iterative design comparisons produced during the Generative Design Studies, was used to inform the development of the Life Cycle Inventory and subsequent Lifecycle Analysis. This data analysis provided direction in identifying those elements, within the Lifecycle, most impactful to environment. This was essential in the circular process of informing and improving the next generation of product designs for production using the Integrated Platform. This historical data is a driver for incremental and continuous improvement.

One area which is often overlooked in the integration process is that of the Human Being to the technical platform. This has been reinforced from personal experience in manufacturing industry many times over the years. One can develop the strongest of technical solutions and platforms, but without the appropriate education, training, attitude and management support, the system is destined only to work up to a certain level. The Humans' ability to take the system and use it creatively thus leveraging all the creative potential is paramount to the success of any such endeavor. This was also an element during the practical development of this platform, especially during the more challenging phases. One requires all the above elements to maintain a positive momentum and extract the ultimate potentials of the system.

The future extension of this platform to full scale manufacturing can be seen in Fig. 101 which illustrates how the Platform would be integrated into a manufacturing system.

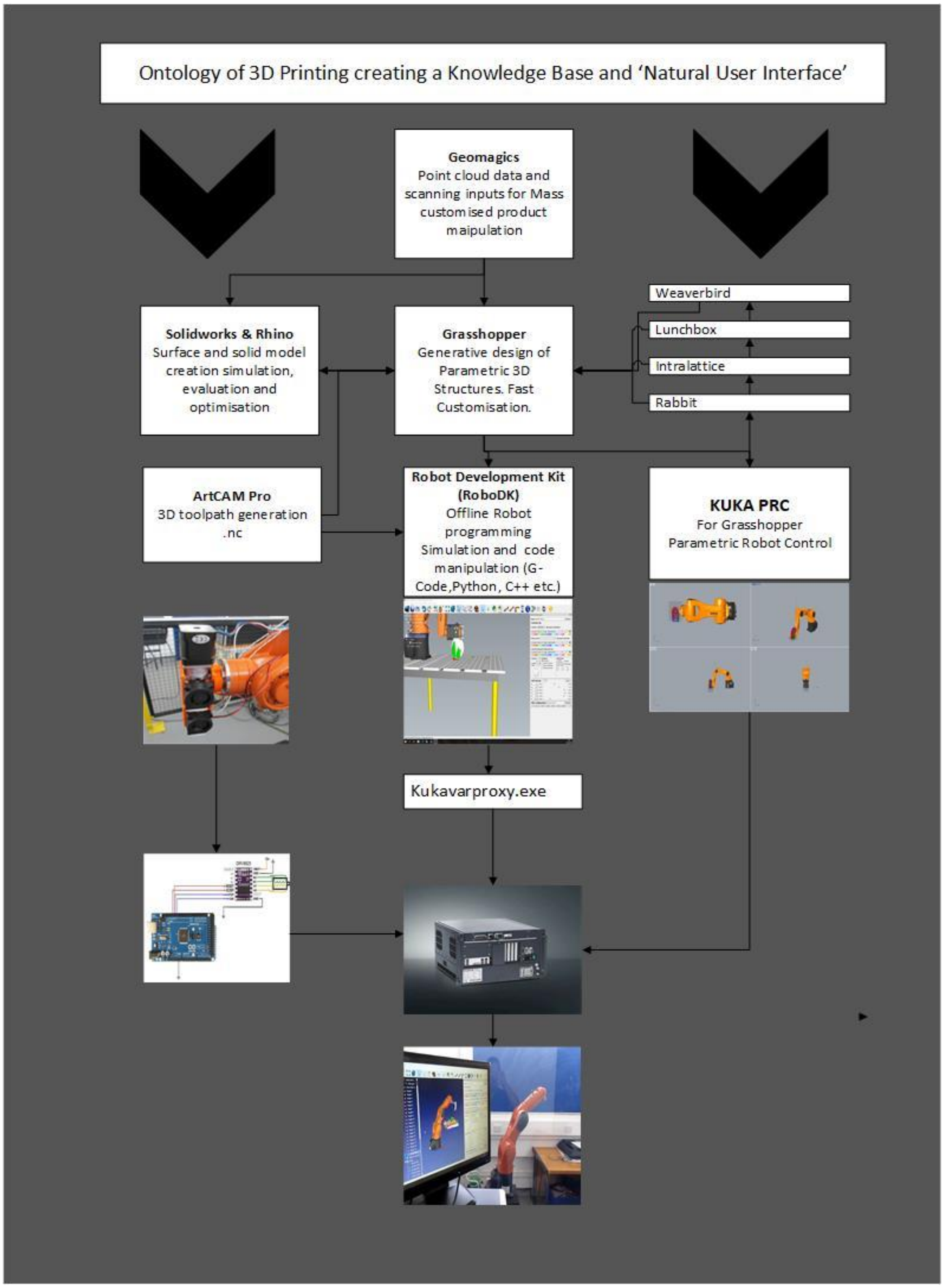


Fig. 79 The hardware integrated with the control and software applications (Fox.A,2019)

Simulation of the robot print path using offline programming software will be achieved using RoboDK (Robot Development Kit) environment. The design, evaluation and simulation of furniture using digital media is still largely achieved by employing traditional techniques for manufacturing and assembling the products.

In using fast curing materials in conjunction with changes in orientation it may be possible to eliminate the need for supports. It may also mean that we no longer have to build the item layer by layer through conventional slicing. This approach could also be extended to the use of tool changers or a number of robots working in parallel, using several different materials.

The Software Development Kits (SDK), Application Programming Interfaces (API) & Integrated Development Environments (IDE) are particularly important in allowing the online and offline programming of the Robot Arm and the control of the Print Extruder. Development work can be done offline while the robot is operational allowing much greater flexibility and efficiency.

Often SDK's come packaged with both API's and an IDE.

- SDK – Complete development environment
- API – A single Interface
- IDE – Helps you to write programs

The SDK should be flexible amongst a good cross section of Robots with the ability to offer a range of programming languages to enable the robot to be used with a large range of applications.

RoboDK was selected as the SDK for the development of the robot printing applications as it allows for the use of a number of languages:

- Python
- C++
- C#
- MATLAB

It also allows for:

- Offline Programming and robot simulation
- Allows verification of the project feasibility before going online
- Can be used on many different Robot Brands

- Can be used in conjunction with CAM applications
- It is affordable for use in a industry such as furniture making

RoboDK is also extremely flexible for 3D printing development utilising code extracted from a number of sources:

- Conventional slicer software
- CAM generated curves and surfaces
- Scanned point clouds

It can also be customised using Python high level coding.

Programming of the tool print paths using a high level applications can make the operation of the robot system a lot easier. They give access to advanced functionality much more quickly and reliably than using specific robot coding e.g. Rapid (ABB), KRL (KUKA), JBI (Motoman) or Karel (Fanuc).

The choice of Language is very dependent on the end goal of the programming. They do allow you to reuse code with different Robots, use debugging tools and add functionality to the robot by using software libraries.

4.8.1 Programming language assessment

The choices may consist of the following:

- **Python**

Recommended for new robot programmers.

Strengths :

- Easier to learn and read
- Access to many powerful libraries
- Quick to write useable and re-useable code
- It is very popular so lots of help is available
- Best for small to medium Robot Programming Projects

Weaknesses :

- Can get messy for large projects
- ‘Jack of all trades and master of none’

- Hard to spot errors as it is an interpreted language

- **C# (C Sharp)**

One of the most widely used programming languages developed by Microsoft in the early 2000s

Stengths:

- Relatively easy to learn and integrate with large projects
- Large quantity of libraries available
- Free Development environment (Microsoft Visual C# Express)
- Microsoft Visual Studio has good development tools
- Runs on .NET Framework and is highly interoperable

Weaknesses:

- Software development is limited to Windows
- Can't be easily deployed to non-windows computers

- **C++**

It is an object orientated language which is based on the C language. It is a performance based language with easily organised code. Best if you need high performance or to interact with low level robotic hardware.

Strengths:

- Potential for high performance
- Access to lots of libraries
- Lowest level programming language above Assembler
- Libraries for robotic hardware components are often written in C/C++

Weaknesses:

- Takes a lot of time to learn and to code properly
- Usually requires a lot of debugging
- Writing programs takes a considerable time

  Third party libraries are difficult to use

- **MATLAB** (Matrix Laboratory)

Not just a programing language but an entire programming environment. Widely used by engineers to analyse and simulate their robots. Over time interfaces have been created to control physical robots, but the process is very convoluted.

Strengths:

- Good for data and kinematic analysis
- Quick to write useable code
- Robotics toolbox is widely used
- Allows complex simulation

Weaknesses:

- Not designed to interface with physical robots
- It's expensive
- Not easy to share code as other person needs to have MATLAB
- Not as many third party libraries as other options

The choice of programming language for this project was made taking into account the nature of the programming work required for this project and the timescale for completion, it has been decided to use Python as the programming language of choice due to its ease of learning and the fact that it can be easily read in small scale programming exercises. It is also well suited to use with the Arduino control boards and associated equipment. Python is a common programming language for use with RoboDK and also the Uarm Swift Pro (Desktop Robot) IDE, postprocessors, drivers and (Github) applications libraries. Although it is not a compiled language and hence is slower than C++, Java, MATLAB etc. In the context of this project the execution time does not really cause any issues.

5 Chapter 5 Sustainable Contemporary Aesthetic Furniture Forms

5.1 Aesthetics

The word ‘aesthetic’ originates from the Greek ‘aisthitiki’ meaning perception through sensation. It may be defined as being related to the enjoyment or study of beauty. It is subjective to a certain extent, since there is no standard by which levels of beauty or ugliness can be accurately gauged. The perception is largely governed by the individuals background, experiences and also to some extent gender (*Yihang B., et. Al.*, 2018)

In furniture design & development it is essential for the product to possess an alluring visual appeal. This family of products has a very visceral connection with the end user and aesthetics is a key product feature in sales and deliberations when considering integrating it into their personal environments. Aesthetic appeal was traditionally achieved by sketching and the incremental transformation of form, function and fitness for purpose by the human designer. Sketching is however limited by prior personal experience and as such can be influenced by familiar routes as opposed to the development of unmapped pathways.

These influences have been the subject of research when examining the role of autonomous generative design and its ability to produce multiple design iterations quickly, while also establishing a platform for the evaluation of design performance (*Camargo M.,* 2016 & *Crilly N.,2017)*.

Generative design has the potential to beautify product designs by creating extraordinary aesthetics through the application of shape grammar algorithms to manipulate and develop geometries.

Some attempts have been made to quantify aesthetics. One early example was Bikhoffs (1933) quantitative theory to measure aesthetics with a simple formula:

$M = O/C$

where:

O - order of the object

C - complexity of the object

M - aesthetic measure of the object

This implies that orderly and simple objects appear to be more beautiful than chaotic complex objects. These two characteristics are often regarded as two opposites, with order playing a positive role and complexity playing a negative role in the aesthetic nature of the product. The more effort a human visual system makes in assessing an object, the more complex the object is.

Fig. 80 Mondrian inspired chair, colour, rhythm, symmetry, simplicity of form

(Designer: Mondrian.P, 1872-1911)

Color perception is closely related to aesthetics, and especially color harmony is commonly used to evaluate elements of aesthetics (*Nemcsics A*., 1980)

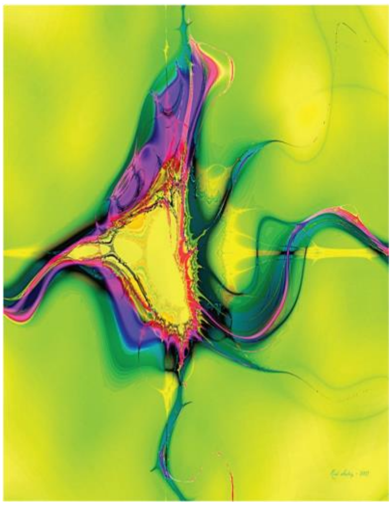
Mondrian inspired chair illustrates the many other elements affecting the perception of aesthetic quality including issues such as symmetry, contrast and rhythm which combine to create harmony. The resultant forms can be seen in numerous natural structures where proportional rules such as the Fibonacci Sequence (Golden Section, Divine Proportion) are prevalent.

Digital art has a great potential to become increasingly expressive and humanised with the development of artificial intelligence and machine learning, producing unique art and structural solutions. Current advances in deep learning and artificial intelligence have created significant opportunities for breakthroughs in aesthetic generative design.

Many different drivers have been researched since the 1970's for the generation of original aesthetic forms, examples being:

Benoit Mandelbrot (1924–2010) fractal generation of art producing beautiful forms which could not easily be described by conventional geometry

(*Mandelbrot B*, The Fractal Geometry of Nature (1982))



Yellow Dreamer Singh G. Transforming fractals, 2014

Fig. 81 Mandelbrot Fractal

Lindenmayer (1925 - 1989): L-systems natural forms

(*Lindenmayer A*, (1990))

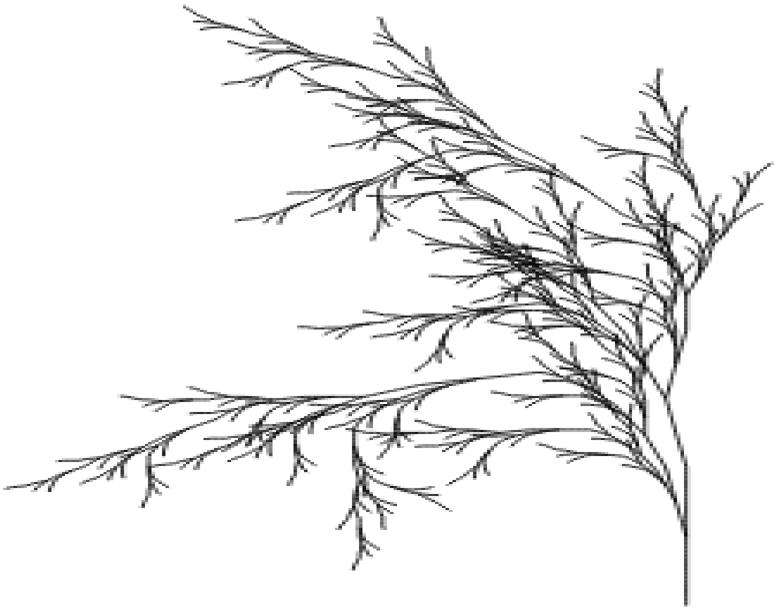


Fig. 82 Lindenmayer 'plant' form

Cellular automata (1940's)– John Von Newmann (1903 – 1957) &

Satislaw Ulam (1909 – 1984)

(*Von Newmann J*, (1960))

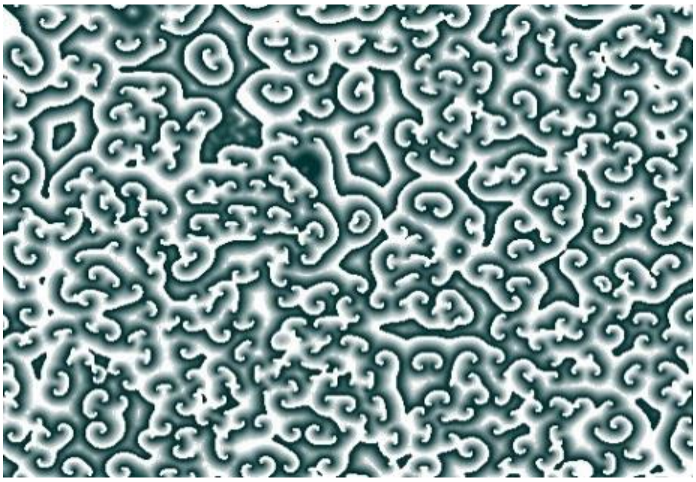


Fig.83 Cellular automata : Belousov-Zhabotinsky

Some of the issues restricting the use of computers for design concept creation are their current requirements for structured and exact data whereas at the early design stage this information is often unstructured and nebulous. Furniture designers' use of computers is still limited largely to digital representation using the computing power to increase human designers yield and flexibility. Processing power and computer capabilities have however progressed considerably with the establishment of cloud processing. This progression has empowered designers in the creative process with the ability to undertake the entire creative process without direct conception by the designer. Despite protestations from traditional designers, the utilisation of Computational Creativity Approach (CCA) allowing computer applications to create shape iterations not directly envisioned by the designer will be a paradigm shift in the future of furniture design (Gabriel A*.,* et al*,* 2016) The design rules could be responsible for the generation of a variety of basic designs with deep learning methods helping to enrich the design with unique design styles. Each design will satisfy the design principles and will also possess a distinct design style. The framework of rules and aspirations can also preserve, to some extent, the designers' style preferences. When designers discard design solutions they must have a set of subconscious guidelines and constraints. By selective filtering of the iterations other styles may be created which were outside of the designers' imagination and immediate experience. These designs may be superior or unique adding aesthetic value to the products.

Quantitative assessment of aesthetics often consists of two steps:

- Aesthetic feature evaluation
- Decision making based on structural features
- Representing the products fitness for purpose

The results can be either binary or can be ranked and weighted to assist the designer in objectively selecting designs, combining the judgements of the human designer with the automated processes of the generative software thus producing incrementally improved design solutions over a period of time.

5.2 Generative Design for Aesthetic Products

Significant applications of generative design in Architecture have been noted but its application in product design is currently not so prevalent. Generative design can produce iterations in their apocryphal form, utilising a framework created for this transition by the designer including elucidation of the 'Brief' and the rule-based stratagems to generate resolutions. Transitioning from human centred design to a hybrid activity while also engaging the potential of machine learning would enable the hardware to 'learn' the design space and procedures employed within it built upon historical solutions without the necessity for direct human guidance. Assisting the Human's resourcefulness and productivity Generative Design enables the identification of inconsistencies, weaknesses or potentially expand the efficacy of designers through the IOT linking of devices providing feedback on product quality from both the pre-production virtual testing and usage phases of the life cycle, fundamentally changing the way things are designed and optimising speed to market. This of course can be extended and integrated to leverage the benefits of other aspects of the Industry 4.0 digital platform facilitating data driven planning, manufacturing and maintenance.

The resultant designs often seem to take inspiration from natural forms and resemble Art Noveaux forms

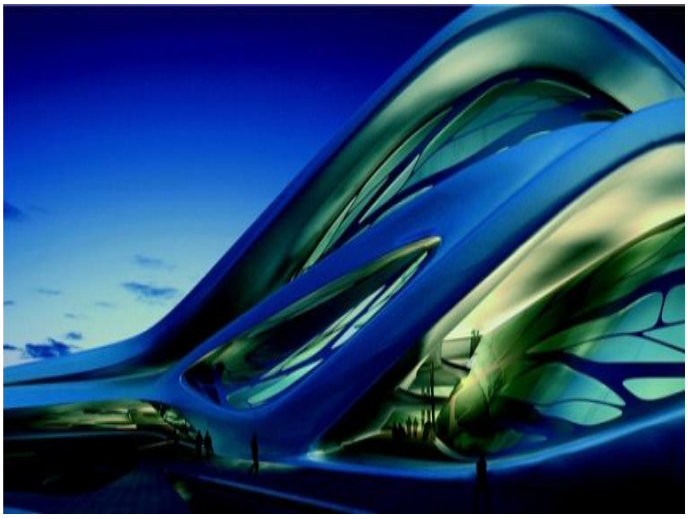


Fig. 84 The Performance Arts Center in Abu Dhabi by the Iraqi Architect, (Zaha Hadid, 2008)

Fig. 85 Sinuous Art Noveaux architecture at
Casa la Fleur De Fenoglio Torino Italy

Generative design can be so unconventional that human designers do not have the cognitive capacity to design in the same way and as such the generative results often far exceed the utility of comparative solutions developed through traditional design approaches. The example below shows the Airbus Industries generative cabin partition which achieved an additional 30% reduction in weight when compared to the best human designed solution. In this case the iteration is extremely angular and not at all symmetrical.

Fig. 86 Airbus Partition Panel, generative iteration, 2019

The challenge is to make systems that designers want to use in order to investigate the potential for performance driven generative design to facilitate negotiation and integration of multi-disciplinary design teams (Cagan J, et al, 2005) Many companies are reticent to invest in premature technologies and would rather hire an additional designer to assist in tried and tested traditional design methodologies (Zobinska M, 2014)

The Furniture Industry is not without a considerable number of sceptics holding back these developments, as designers will feel vulnerable by, as they see it, removing a large part of the creative process from their remit, with them artlessly left to choose between an array of iterations. This is illustrated below in a quotation from a senior contemporary furniture designer in the UK (who wishes to remain anonymous):

" I have always thought of traditional furniture making as a crafted process rather than 'manufactured'. The whole debate of CAD as a design tool is ongoing & thinking/designing at the tip of the pencil always provokes discussion!

I always worry about taking the design process away from the designer and into the hands of AI and some form of common database."

The truth is that there is a need to leverage the potential of cloud computing in the development of customised products with superior performance, unique aesthetic qualities and lean environmental credentials through the evaluation of multiple aspirations concurrently to produce unique results.

5.3 Cloud Based Generative Design

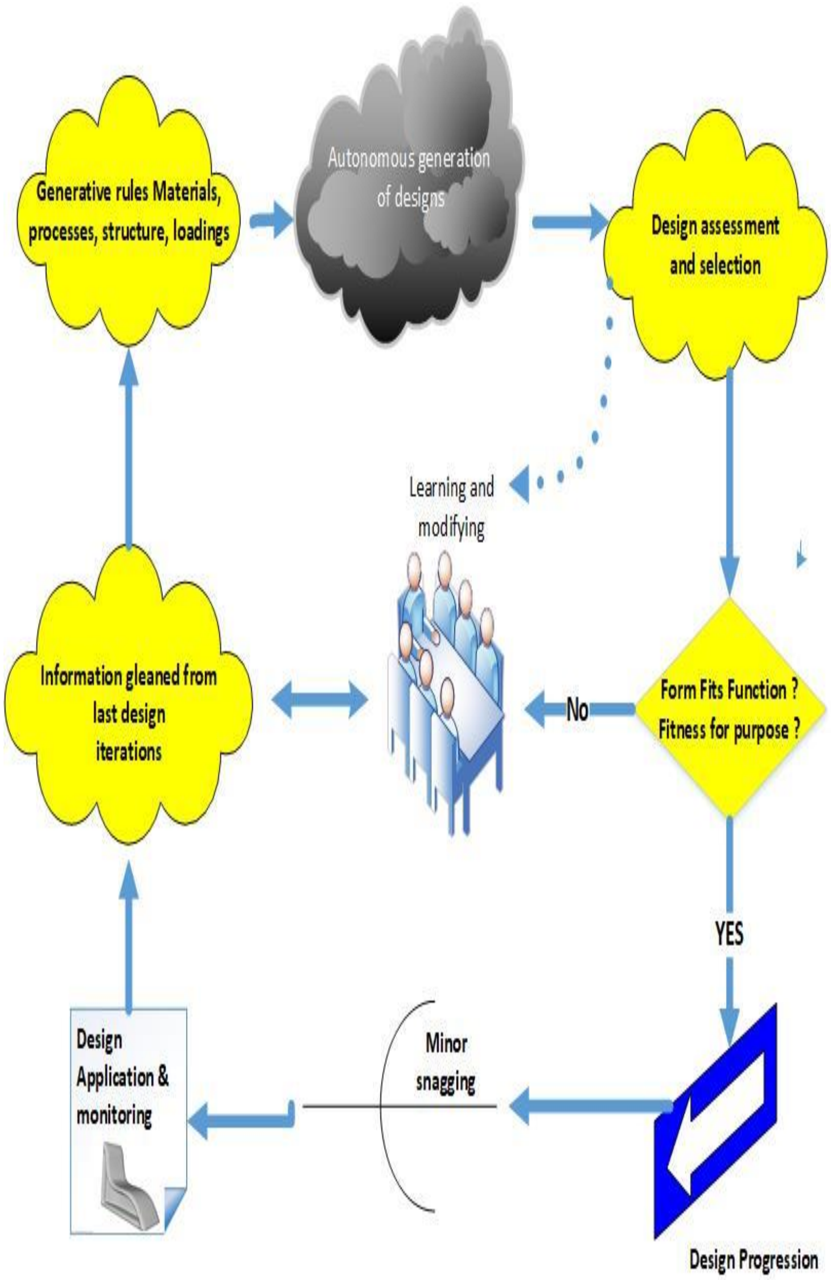


Fig. 87 Design Process flow for generative Design (Fox.A, 2020)

Fig. 88 AI Cloud Based Generatively Designed chair digital representation (Fox.A, 2020)

5.4 Shape Grammar in Generative Design

In the realisation of truly customised aesthetically pleasing products it is essential to be able to quickly and easily manipulate the sometimes complex and unconventional geometry to conform to the clients' exact requirements.

This can be achieved with the use of Shape Grammars. It this case it is being illustrated using the Non-Uniform Rational B-Spline (NURBS) modeler, Rhinoceros utilising a generative design plug-in called Grasshopper.

NURBS is a mathematical model commonly used in computer graphics for creating and representing curves and surfaces. It extends great flexibility and precision for handling both analytic (surfaces produced using formulas) and designer created shapes. NURBS are frequently used in CAD, CAM, and CAE and are part of many industry standards, including IGES, STEP, and ACIS.

Grasshoppers' generative power to create models through designer created shape grammar networks is very powerful. Although the approach to this sort of design is very different to traditional approaches and takes some time to master.

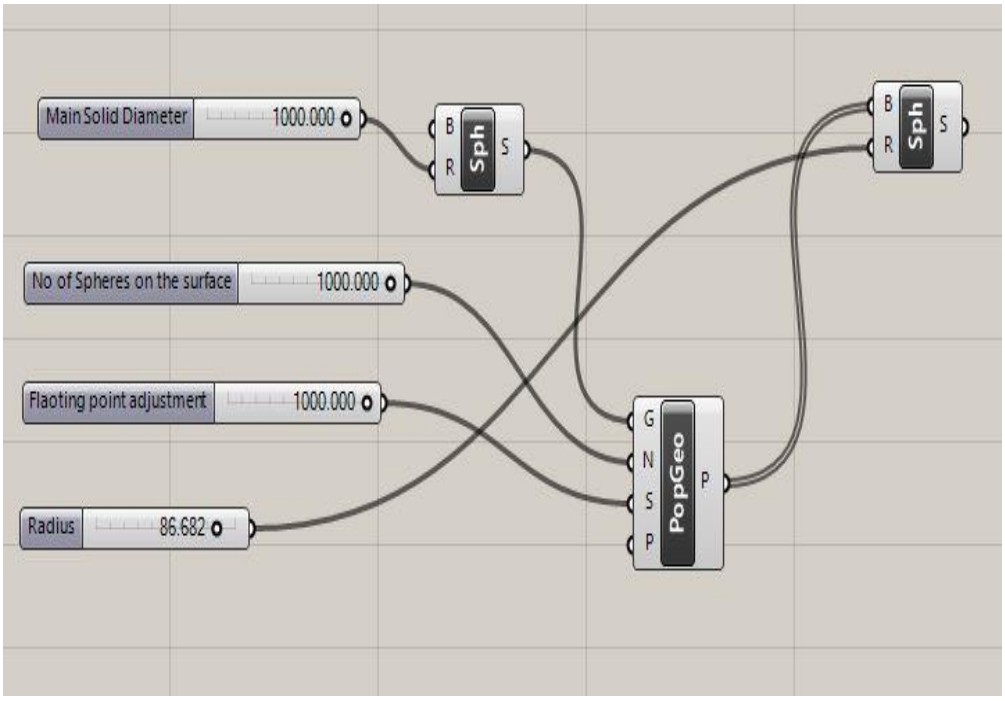


Fig. 89 A screen capture illustrating a very simple Grasshopper Network used to populate existing 3D Geometry (Sphere) with other smaller spheres. (Fox.A, 2019)

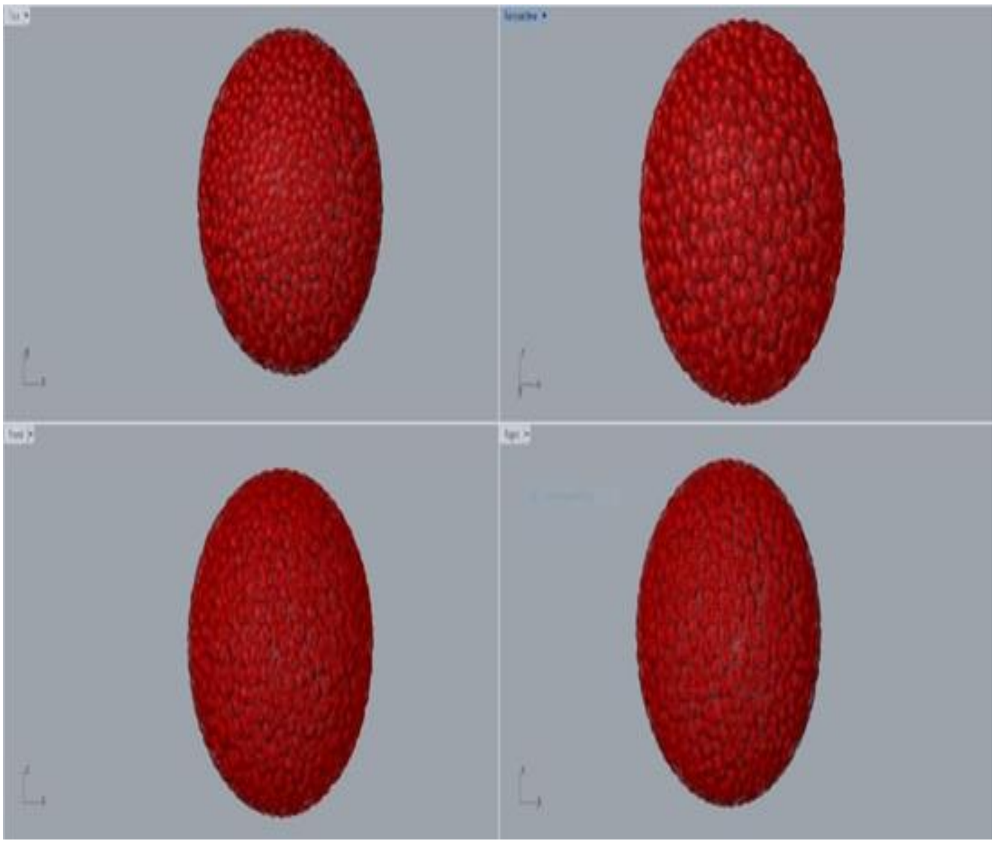


Fig. 90 A Main Sphere populated with smaller infinitely variable spheres (Fox.A, 2019)

The integrated generative design platform was used to design & create a simple scaled example of a 'Bubble Chair' using simple Boolean subtractions to form the shell geometry which was then populated with smaller sphere geometries to give the surface textural feel of 'bubbles'. This was then converted into a printable 'watertight' model. The model is completely customisable using the Shape Grammar Network , both for overall dimension and for the density and size of the outer sphere population.

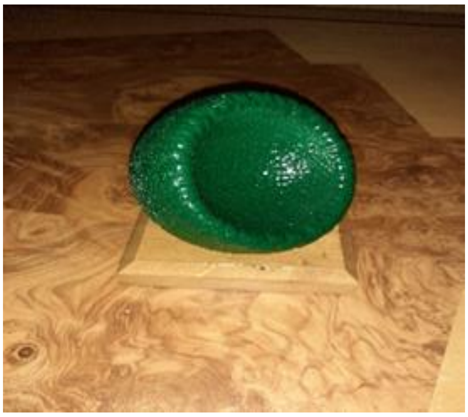


Fig. 91 Bubble chair designed and produced on the Integrated Platform (Fox.A, 2020)

This sort of transformation would be incredibly difficult using traditional design methods.

In practical design terms this sort of approach could be used for producing furniture designs like the one illustrated below:

Fig. 92 Illustration of possible furniture design application using Geometry Population (Shutterstock)

The ability of Shape Grammar networks to edit and customize the AI generative design solutions gives the designer and manufacturer a clear and integrated path to producing Mass Customised client solutions. In the illustration below it is shown that a watertight 3D model of a vase can, using the same base geometry, be completely transformed to a customized product in a matter of seconds.

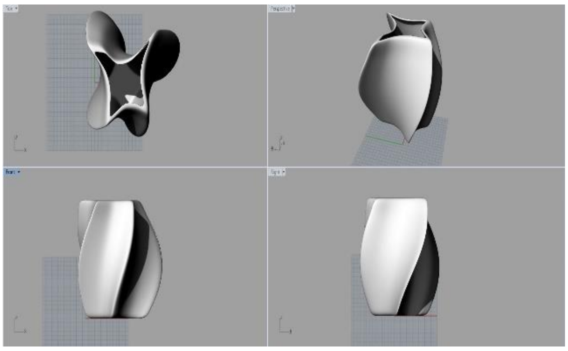


Fig. 93 Original Printable Vase Model (Fox.A, 2019)

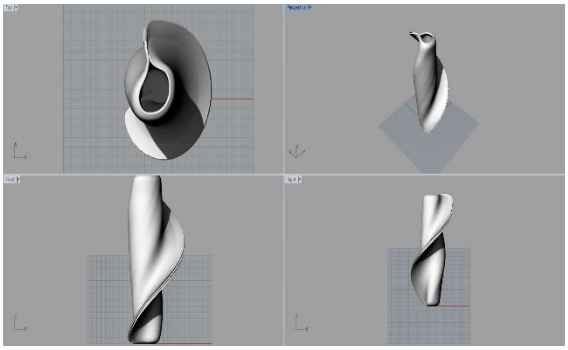


Fig. 94 The original vase customised using Shape Grammar (Fox.A, 2019)

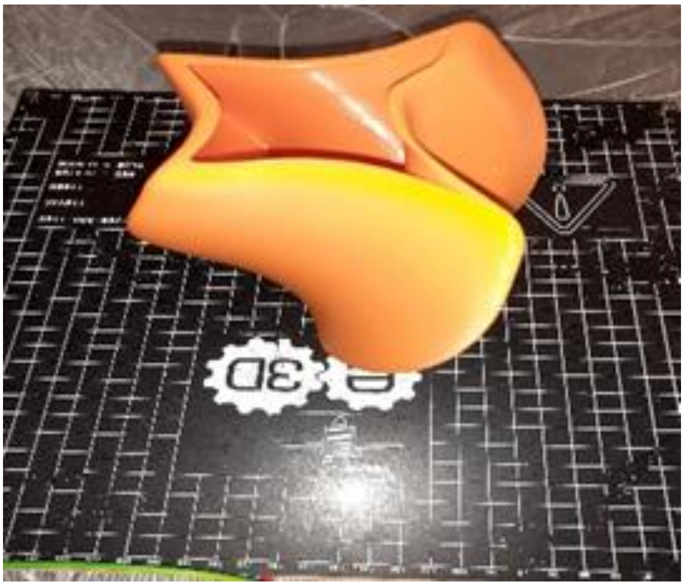


Fig. 95 Integrated platform designed and printed vase iteration (Fox.A,2020)

Other examples were produced to illustrate a small cross section of the versatility possible creating customisable structures with Shape Grammar on the integrated generative Design Platform. The following images show how lattice structures can be graduated and manipulated to allow many different sorts of unique furniture structures to be produced.

The following images show rendered examples of graduated Lattices produced on the integrated platform. These can be manipulated in many ways including fitting them between irregular surfaces and structures

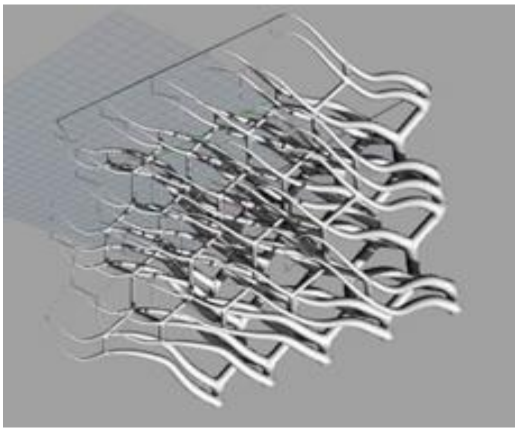


Fig. 96 A rendered example of an organic lattice structure which is graduated from one face to another. Rhino/Grasshopper/Interlattice (Fox. A, 2020)

Fig.97 Two scaled examples were created using the integrated platform to show the basic designs three dimensionally. A Honeycomb graduated lattice table base with clear acrylic top and a honeycomb lattice chair base and back distributed between the irregular seat platform surface and a circular surface at floor level. Rhino/Grasshopper/interlattice (Fox.A, 2020)

5.5 Production Ready Designs

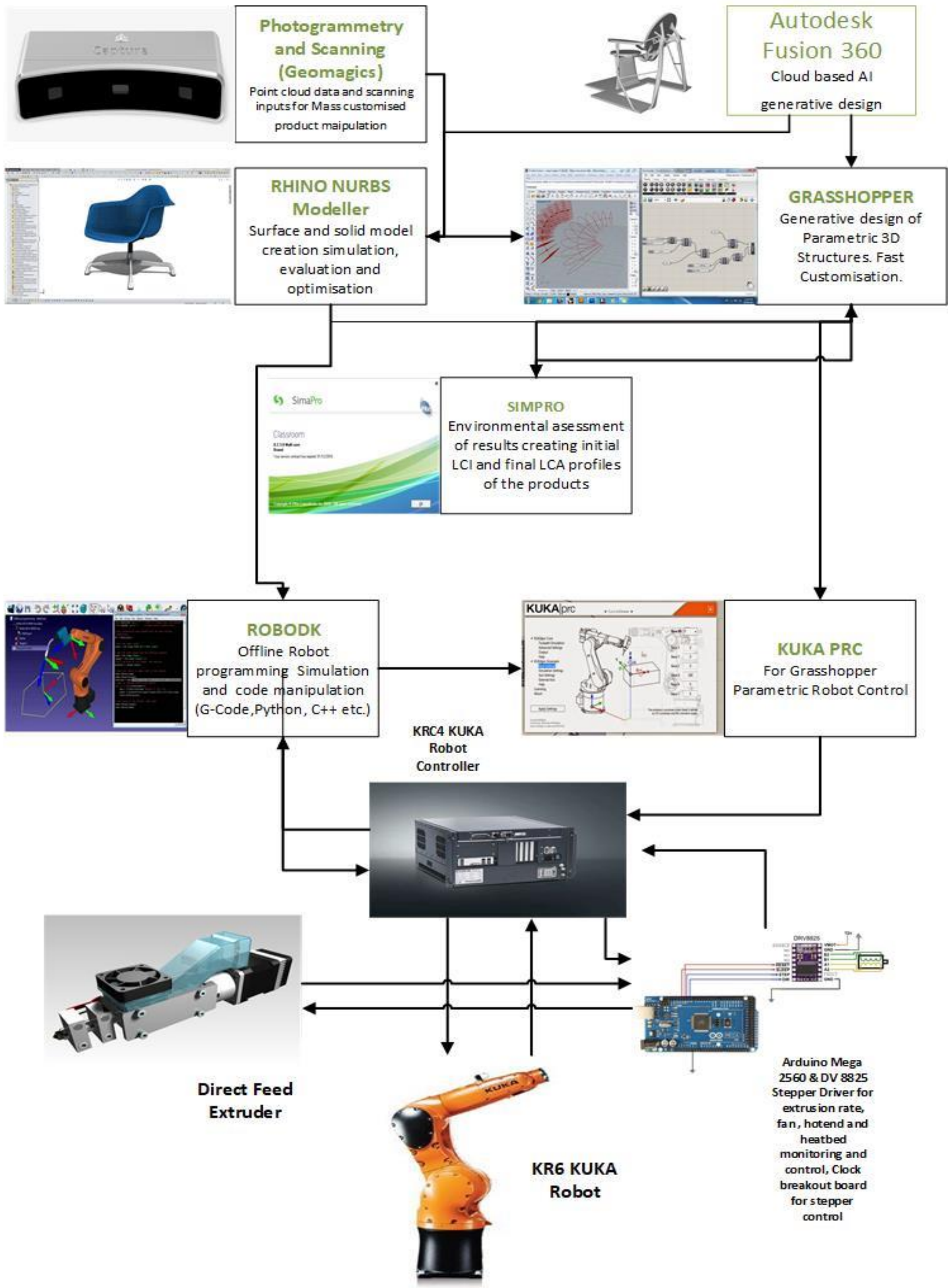


Fig. 98 Schematic of integrated software and robot hardware

(*Fox. A.*,2020)

The design structure developed for work with the KUKA KR6 700 Robot is both flexible and adaptable to many different end uses. It is a small-scale representative cell which can be easily adapted for use with a large range of full-size industrial robots. The Kuka Robot is equipped with a screw fed extruder to allow for high material feed rates and a rapid heating 110 volt build platform, thus reducing setup waiting time and allowing for fast build rates. The Extruder is supplied with pellets by hopper feed allowing large amounts of material to supplied to the extruder without pausing production. The extruder and build platform are both controlled by Arduino microcontrollers, allowing control of the Initial setup period for heating, extruder feed speed (stepper motor), Hotend / Build platform temperatures & control of the cooling fans.

The interface between the design software and the Robot is currently via Robot Development Kit (RoboDK) in which the cells are created and the models are integrated for printing to produce the KRL code required for the Robot. Bespoke Python code and GUI then monitor the robot equipment and compiles the code for execution. The integrated software platform allows for the creation & use of existing 3D model geometry, scanned point cloud data to produce models or geometry produced using Shape Grammar. All designs then can be further customised using Shape Grammar in the Grasshopper environment.

When modelling printed objects in Rhino/Grasshopper/Fusion it is essential that the object to be printed is 'watertight' in effect this means that all inner faces of surfaces produced are not visible. Only Manifold models will print successfully. The definition of a manifold geometry is one which does not share edges on two faces. This could be the result of inconsistent modelling or overlapping objects etc.

To be printed correctly the meshes must be orientable, where faces are composed of face normal which follow the same directional logic. The geometry must also not be comprised of intersecting non-Boolean objects.

Together with these considerations the usual considerations for 3D prints using different technologies apply. For example, build volume to machine capacity, minimum wall thicknesses, the resolution of the print is matched to the capability of the machine and the specific techniques employed.

Parametric Robot Control (KUKAPRC) can also be used as an essential and crucial link between the design process and manufacturing. New manufacturing techniques, assembly strategies and new materials often prompt step changes in design practice.

Before the 'digital revolution' designers used to deal with complexity by breaking down the product into separate parts and creating part to whole assembly strategies using scale models, prototyping and drawings. These were then transferred to suppliers to interpret and fabricate the elements contained within the Bill of Materials (BOM)

This process was quite limited to orthogonal shapes and was generally very constrained when dealing with complex geometry. The digital revolution has transformed this by linking design outputs directly to manufacturing. These have the potential to be further enhanced by providing robots with coded instructions regarding the artefacts to be produced, e.g., Ontology & AI.

Up until quite recently the technologies employed consisted of Computer Numerical controlled technologies such as Laser, Plasma, Waterjet and Subtractive machining to name but a few. These applications were still limited by their restricted capacities. Industrial Robots are now being seriously considered as the platform for far more flexible manufacturing. Their additional degrees of freedom and the ability to move the platforms to extend range and capacity make them a logical platform for the future. This coupled with the flexibility to easily change the function of the arm give them the ultimate utility for future step change manufacturing. The simple example below illustrates the ability to control the robot arm movements graphically both in the offline simulation and subsequently when connected direct to the robot controller.

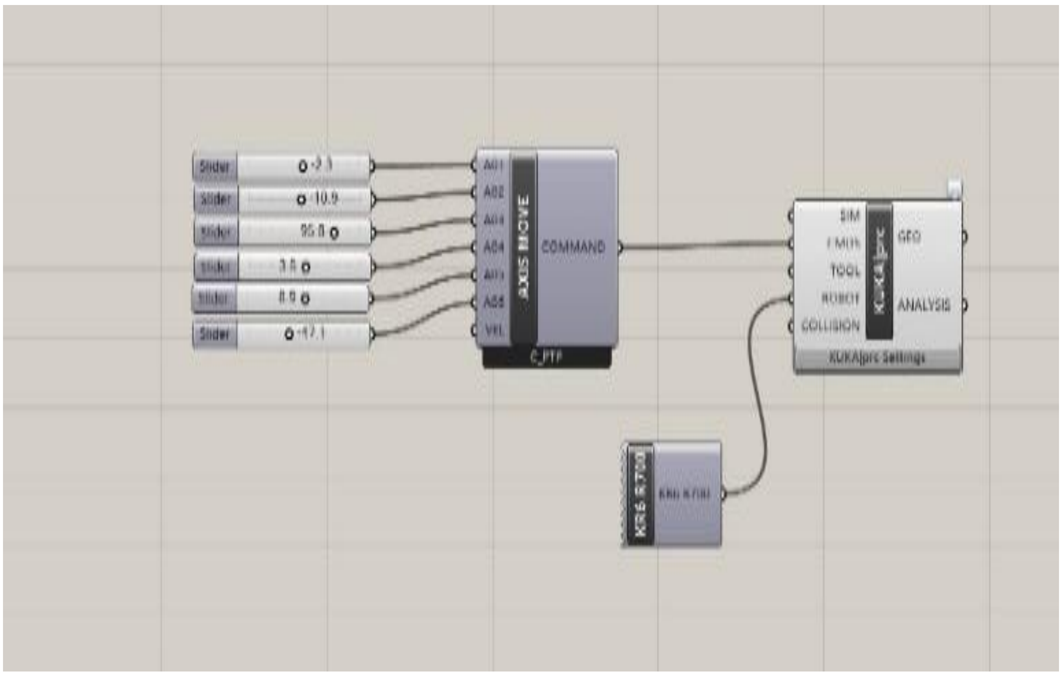


Fig. 99 Grasshopper network for creating robot movement, Kuka KR6 (Fox.A, 2020)

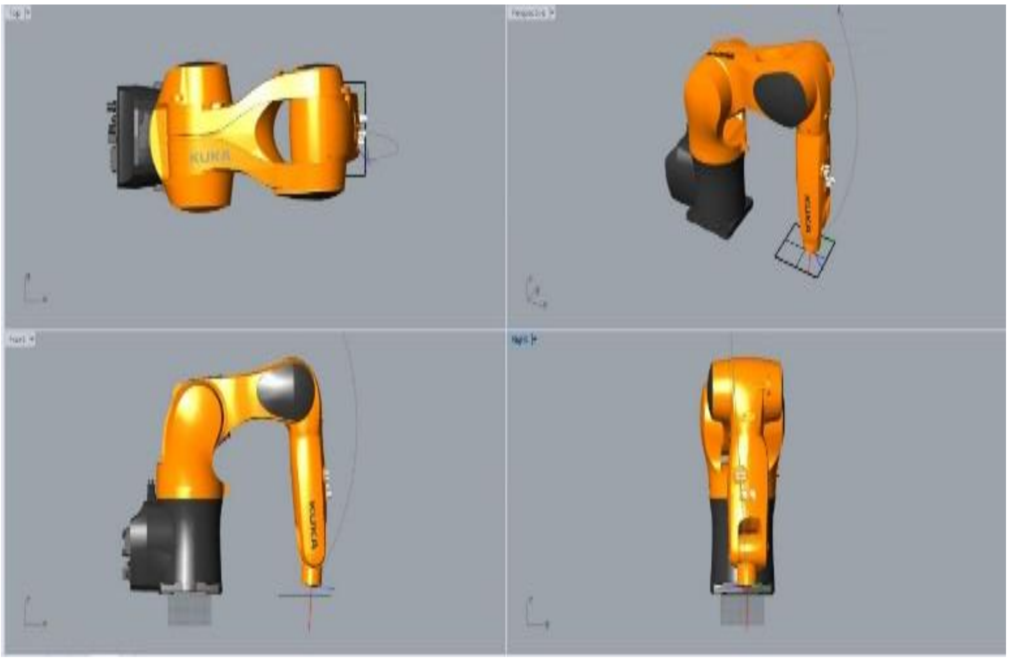


Fig. 100 Kuka KR6 Robot movements illustrated in Grasshopper Design Spaces (Fox.A,2020)

Another alternative is RoboDK plugin for Solidworks/Grasshopper/Fusion allows one to combine the specialist modelling features of Solidworks/Grasshopper/Fusion with the offline and simulation properties of RoboDK. The advantage of this link is that one can load 3D Solid Models from Solidworks/Grasshopper/Fusion directly to the robot cell. The alternative and most exciting addition is that robot programs can be created directly from groups of points, lines or polylines. Alternatively, AM G-code programs can be created and loaded direct to RoboDK for post processing by a wide range of Industrial Robot Arms.

The Autodesk Fusion 360 platform is primarily a Computer Aided Manufacturing platform the ongoing development of which has led to the incorporation of a Generative Design Application. This application has several clear stages in which the solid model of a product can be entered into the Generative Design Environment and have parameters added to it which cover manufacturing methods, range of materials to be considered, loading, design requirements (material reduction, structural aspects etc.). It is possible to do simple preview assessments of the potential outcomes on a PC workstation, but full processing of all iterations and constraints requires a significant amount of computing power and may take some considerable time to process the Generative design.

5.6 Full Scale Production with AM

Full Scale Production with Robot Based Additive Manufacturing, aim of this research, is to produce a coherent system to be used in the commercial manufacturing of Customised Sustainable Furniture Products in a fully automated manner. The system has been designed to integrate with other commercial software used in the day-to-day control of factory operations. The illustration below shows how the flexible customised robot cells will operate within that commercial environment and planning for the manufacturing schedule for a truly unmanned factory.

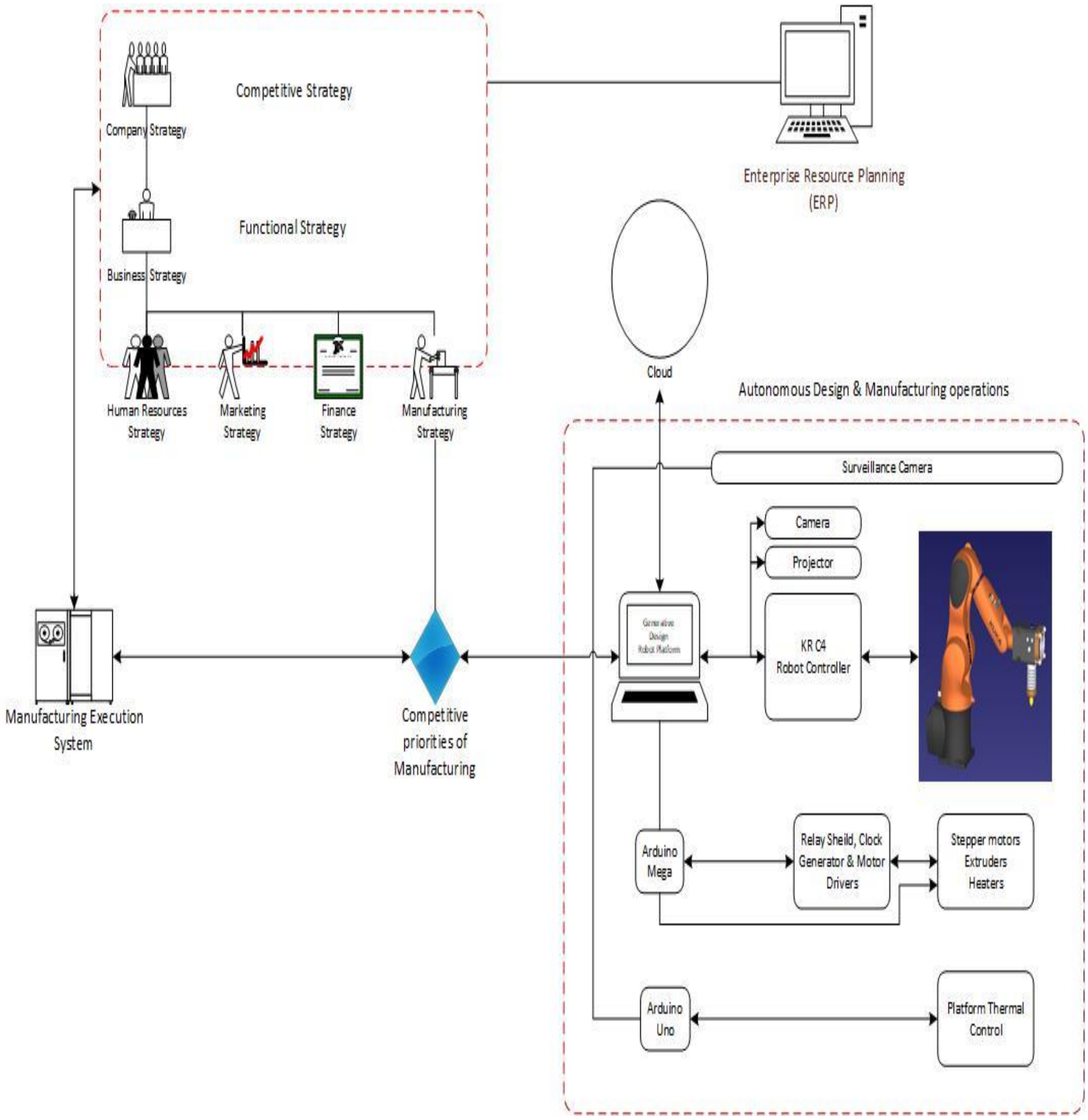


Fig. 101 Schematic of Robot AM Manufacturing integrated into a Factory Control System with Fringe Projection QC Element (*Fox A, Zhang T,* 2021)

5.7 Illustrated Generative Example

Approaches to design methodology alter quite considerably in traditional human design activities, this is no different with Generative Design. The skill of the design technician in manipulating the software platform and input parameter rules has the potential to create truly unique solutions to those briefs.

With aesthetic form as the major focus the following case study illustrates the outcomes of an approach using preserved and constrained load bodies only. This approach demonstrates the creative potential of Generative Design most effectively.

Some potential approaches being:

- Full structure tightly constrained
- Preserved and constrained load bodies only

The outputs can be focused and prioritized towards:

- Minimising of Material Mass
- Maximisation of Structural Stiffness

In addition to aesthetics the Finite Element Analysis (FEA) will give a visual interpretation of the structures performance characteristics.

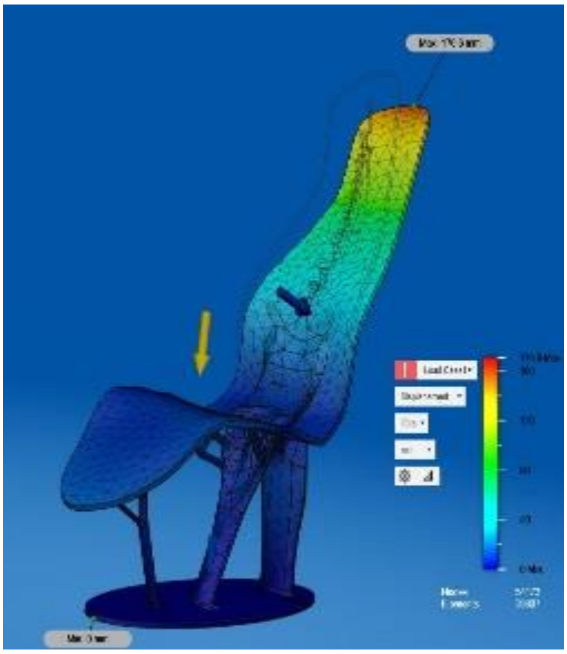


Fig. 102 FEA of the iterations. (Fox.A,2021)

The case study consists of a chair design whose structure has been developed using a solid model representation of the human form. This solid model can be manipulated to the pose that is required for the product development.

Fig. 103 Articulated Manikin used to create surfaces. (Fox.A,2021)

In this case ergonomic surfaces are produced to support the body.

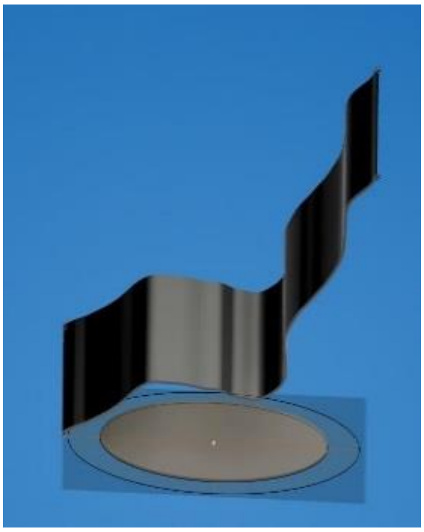


Fig. 104 Basic surfaces created (Fox.A,2021)

From these basic surfaces and bodies one can produce tailored surfaces by projecting the desired geometry onto the surface and creating separate contoured bodies onto which loads, aims and constraints can be applied. Additionally, in this example a base body was created to represent the contact area with the floor and may be locked by a number of means in that position. This may be seen on the load visual as a small padlock symbol.

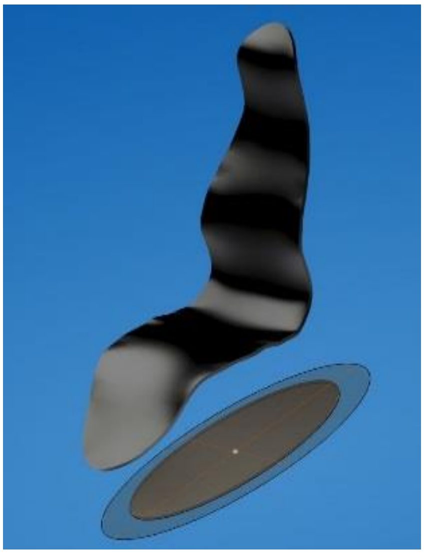


Fig. 105 Trimmed and formed surfaces (Fox.A,2021)

All of these bodies are designated as Preserve Geometry (Green) which essentially means they will remain intact and unaffected by the generative process. The yellow geometry represents the original start geometry. While the arrows signify applied loads (yellow) gravity (blue) load applied to the geometry. Following on from the creation of the preserved geometry bodies, loads, forces and moments can be allocated to the bodies as a 'load case'. These loads can be seen represented by blue arrows in the diagram below. The small white padlock on each base body indicates that it is fixed in that position. This can again be varied to a pivot fixing or frictionless contact fixing to ensure that the most accurate scenario is produced.

Fig. 106 Load Case, Aims and Constraints applied (Fox.A,2021)

As the Generative system does not know the end use of the structure it is creating, it is necessary to add additional geometry bodies which will limit the growth of the structure in certain areas. In the illustration below the red bodies represent areas which are off limits when the structure is developed. In this case allowing space for the person to sit, maintaining a free area under and behind the chair structure.

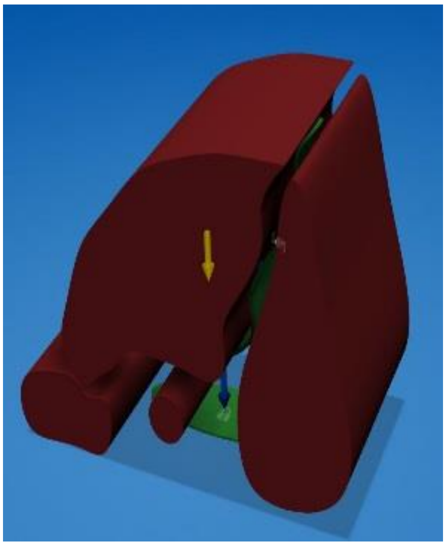


Fig. 107 Additional Geometry added to constrain structural growth (Fox.A,2021)

At this point the Cloud Based AI Generative Design process takes over from the designer to create structures for consideration and further manipulation. These iterations are compared by visual appearance by the designer but the software also compares the iterations graphically for many features including, materials quantity, FEA results, manufacturing methods. These can be selected by the designer depending on their requirements.

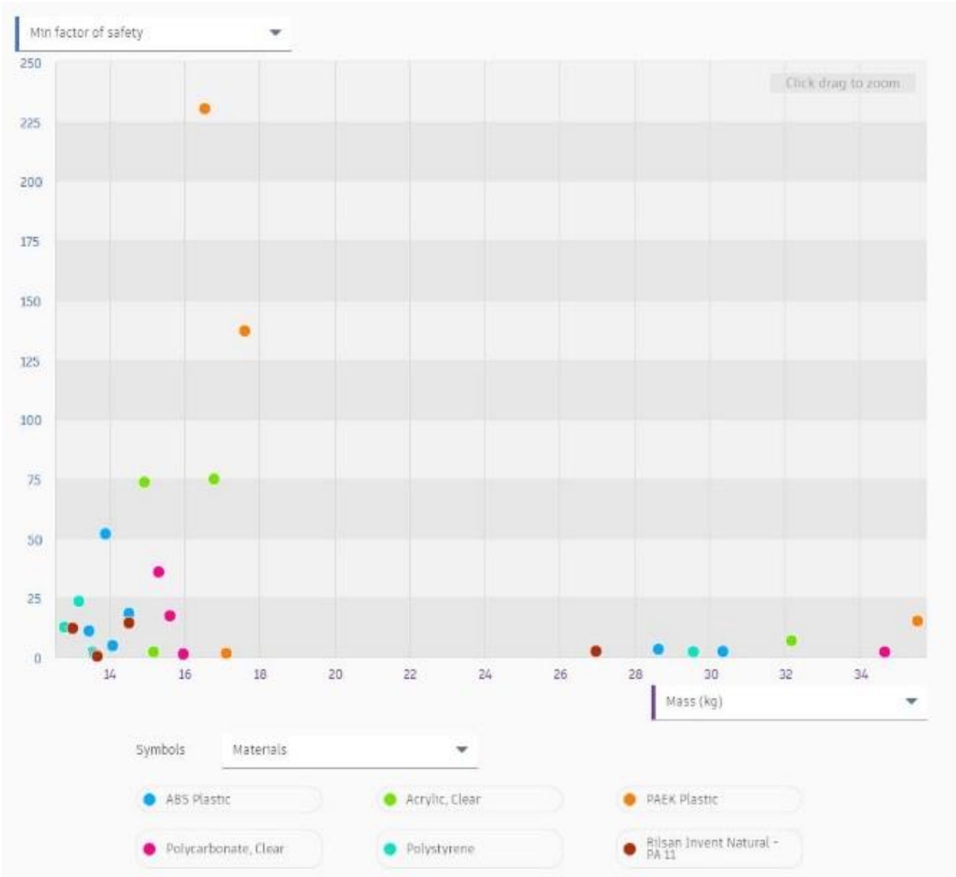


Fig. 108 Designer configurable graphical iteration comparison. (Fox.A,2021)

Fig. 109 Iterations compared by form and KPI measures.(Fox.A,2021)

On selection and final modification of the design it can be further customised with the use of Shape Grammar. The very simple example below illustrates the ability to easily scale the iteration. The same networks can be used with any geometry and therefore once created gives access to those transformations for any design.

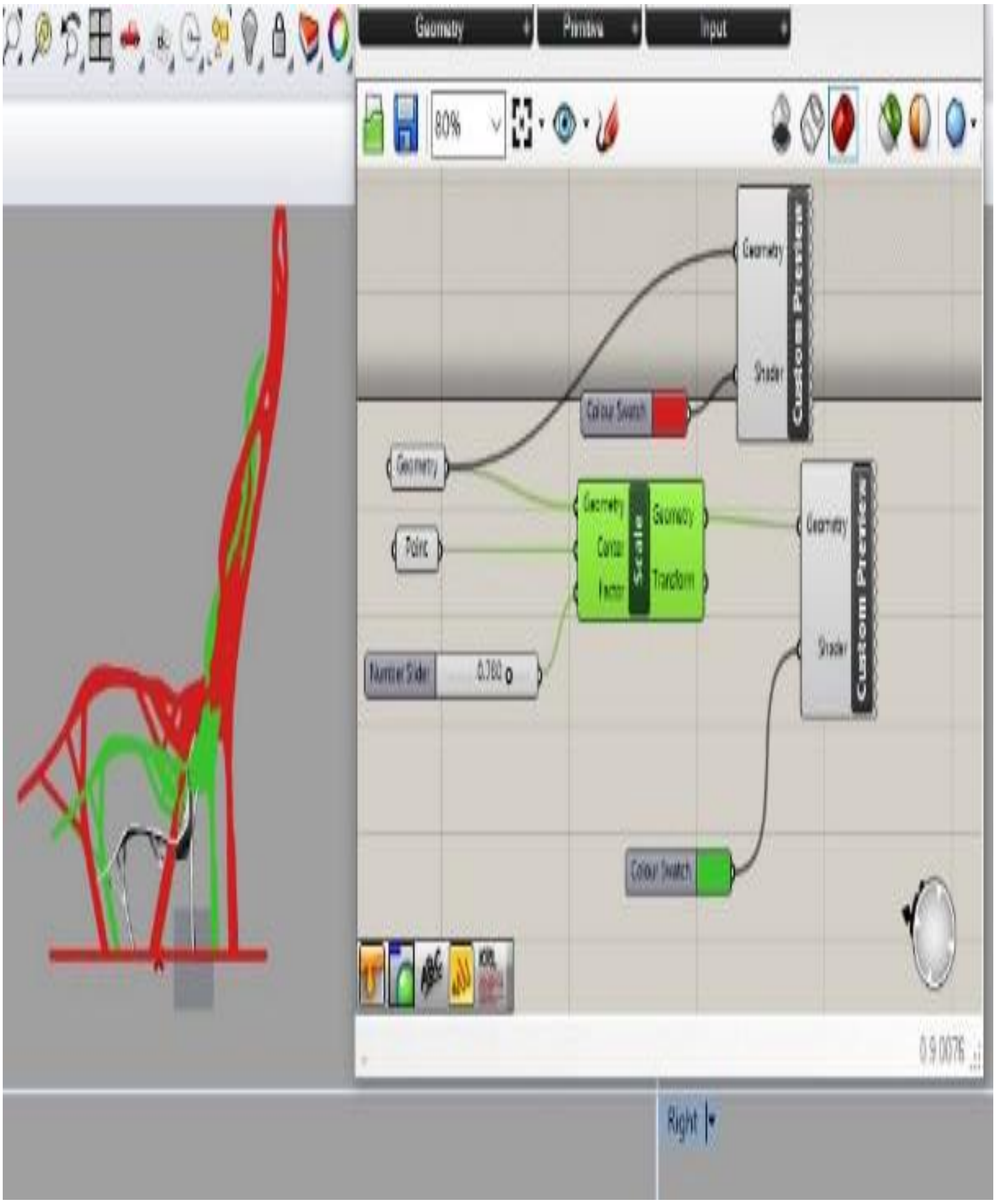


Fig. 110 Simple Shape Grammar Customisation (Fox.A,2021)

The customised design then moves to the Robot Development Kit (RoboDK) environment and is sliced ready for final printing.

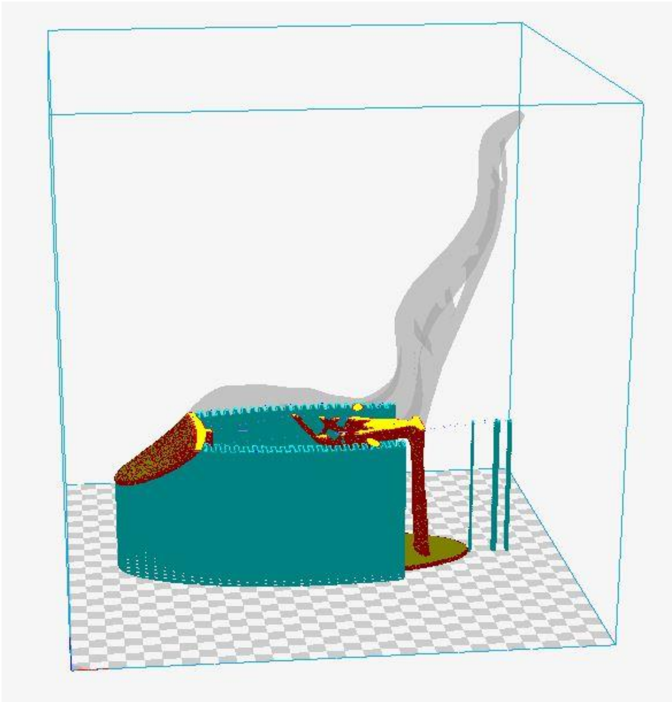


Fig. 111 'Cura' Slicing the Final Design (Fox.A,2021)

Fig. 112 Digital rendered photorealistic representation of the generative scale models (Fox.A,2021)

5.8 Summary

The fundamental change in design practices afforded by cloud based generative design combined with shape grammar customization offers the potential for Furniture Manufacturing organsiations to engage in the Research and Development of unique aesthetic forms, novel and unconventional structures together with materials conservation through, assembly reduction requirements of flat bills of materials and internal matrixing of the structures.

Formerly uneconomic product forms are now viable with the adoption of Additive Manufacturing Technologies and the major constraint of product size is overcome by basing this technology on a robot manufacturing platform.

The future scenario presented for the Robot Based Additive Manufacturing of full scale furniture also allows for the incidental upscaling of the ability to scrutinise the designs from many perspectives enabling a far higher proportion of Right First Time production ready products. The effects & costs of inherited problems from traditional designing in manufacturing will be significantly reduced and hence costs of downstream rectification and amendment will also be minimized.

The fact that common skills are now more transferable across a wide product offering allows for greater labour flexibility and the opportunity to customize products quickly and efficiently without the constraints of traditional setups.

All of these elements can be reflected through LCA to further enhance the low environmental impact profile of these products to prospective customers.

6 Chapter 6 Environmentally Sustainable AM Customised Products

6.1 AM Impacts and Drawbacks

6.1.1 Support Materials

Despite the strong capability of 3D printing to develop designs and structures almost impossible to make using conventional methods, this technology has to employ support structures when creating certain parts of the product. Printing support structures combined with the need to remove them and post process the product, increase lead time, materials usage and wastage levels are also affected by these elements.

Support structures are required in a number of situations and are heavily dependent on the orientation of the parts being printed. The need for support varies depending on the processing method being employed.

For FDM there are a number of rules for the application of support structures.

It is best illustrated with an example of letter forms T H Y:

If the structure has overhangs that are more than 5mm they require supports. Anything over 5mm will be subject to the material slumping. In some cases bridging can be attempted where the material is applied unsupported. This can be seen more extensively in gel printing where the material is two component and is cured as it emerges from the extruder. This is a significant barrier when attempting to achieve 'Freeform' or 'Anti-gravity' printed products.

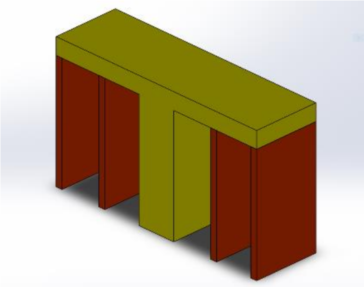


Fig. 113(a) 'T' Support (Fox.A, 2019)

The other common form of support is for arch structures and surfaces between a number of uprights, this type of structure requires 'ceiling' supports as seen with the letter 'H' below.

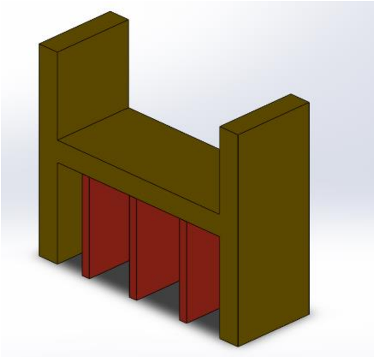


Fig. 113(b) 'H' Support (Fox.A, 2019)

The letter 'Y' illustrates that it may not be necessary to support the structure if it is less than 45 degrees from the print bed surface.

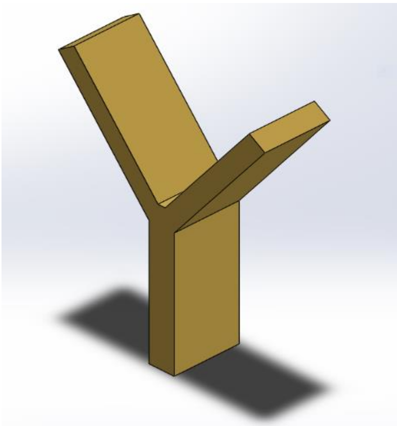


Fig. 113(c) 'Y' Support (Fox.A, 2019)

Applications needing stability and support of a thin object have two basic alternatives.

- The 'Raft' is a thick base layer upon which the part is then printed. It goes right under the part to form a solid and stable base. It is quite often used with the printing of ABS to give a good solid anchored base.
- A 'Brim' around the outside of the component, this is usually only one print layer deep and goes around the outside edge of the component (not underneath).

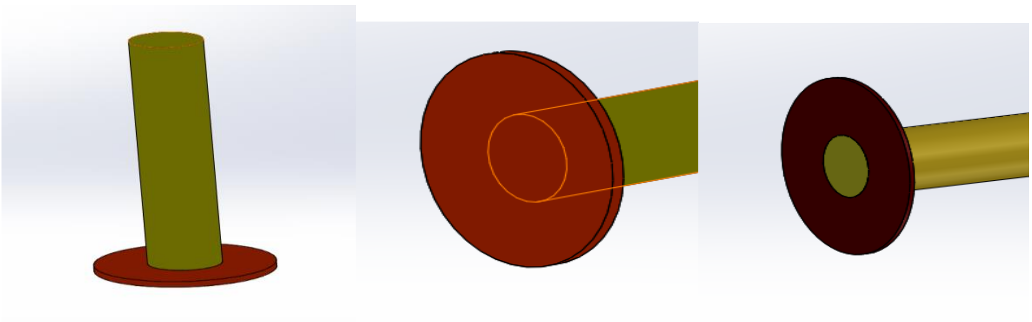


Fig. 113(d) Raft & Brim Support(Fox.A, 2019)

Supports can take several forms depending on what is selected for the product being produced, variants such as the ‘Accordion’ and ‘Tree’ structure can be seen in the image below.

Fig. 113(e) ‘Accordion’ and ‘Tree’ structured support variants. (Fox.A, 2019)

The result of under supported structures can be extremely detrimental to the resultant print, see the image below.

Fig. 114 Unsupported vs Supported print results. (Fox.A,2019)

Where multiple extruders are used a soluble structure can be printed to support the product. This is then dissolved using Sodium Hydroxide and Sodium Silicate solutions. This takes about 30 minutes to an hour to remove the support structures. The subsequent post processing of the components can then take place to give an acceptable surface finish. This may involve chemical treatment of the surfaces using materials such as Methylene Chloride or solvent smoothing together with media blasting at low pressure with Aluminium Oxide, Plastic Beads or Soda Crystals.

Quite often models are then spray finished or post processed further to give the desired surface texture. These elements need to be considered when making a comparison between Additive Manufacturing to Conventional Machining Processes.

Additive Manufacturing also raises a number of new Environmental and Health & Safety issues

6.1.2 Post Processing & Process drawbacks

Post Processing in general is an AM process drawback which affects many of the different fabrication techniques. A key element of the Postprocessing of most products relates to the removal of the support structures. This can be achieved manually by breaking the structure away and cleaning the resultant surfaces. More commonly now the structures are removed chemically using processes such as Volumetric Velocity Dispersion (VVD) in which a suitable solvent or detergent is sprayed onto the product. This process is both time consuming and adds to the Environmental footprint of the AM products. This stage has the potential to be eliminated through the use of Novel Manufacturing Strategies.

In the manufacturing of Furniture, the need for extremely high surface quality and finish is not paramount. Some post processing may be necessary in order to correct and adjust the wave field depth between layers, prior to surface finishing. This surface editing of the AM product could take a number of forms including chemical smoothing (e.g., Acetone etc. for PLA or ABS), abrasive sanding, tumbling or friction/flame polishing. The issue with these being the potential to lose important product features due to the uncontrollable nature of the process. This is one major reason for the increasing popularity of Hybrid AM and CNC applications, where the product is printed and the machine then mills the surface detail to an acceptable standard, while retaining or indeed adding details requiring greater accuracy than AM can afford.

From this point onwards the primary consideration is on aesthetics of the product. There may be a requirement for Surface Finishing which could take the form of dyeing, priming, spray painting or electroplating etc. to achieve the desired end results. This again is an area for future research and development through the use of AM developments such as Voxels through which colors, textures and densities can be modulated throughout the product structure during the printing process.

6.1.3 Novel Manufacturing Strategies

Industrial Robot Based Additive Manufacturing (IRBAM) enable novel manufacturing print paths and orientation strategies. Printing of 3D spline type print paths together with the possibility to change the orientation of the part and hence the orientation of the print material application. Examples of this can be seen in the experimental examples of polymer & weld 3D paths together with robot printing in conjunction with external axis work fixtures.

Fig. 115 Anti –Gravity freeform polymer extrusion, Joris Laarman Lab 2.0

Fig. 116 Freeform Metal printing, Joris Laarman Lab 2.0

A Hamiltonian path is a graph path between two vertices of a graph that visits each vertex exactly once. If a Hamiltonian path exists whose endpoints are adjacent, then the resulting graph is called a Hamiltonian cycle.

A vertex is by definition the "highest point". It is the common endpoint of two or more rays or line segments. Vertex typically means a corner or a point where lines meet. e.g., a square has four corners, each is called a vertex.

Fig. 117 Hamilton Path (Shutterstock)

Fig. 118 Metal Spacestream Chair (Widrig.D, 2012)

Brunel University has a number of robot technology platforms with the potential to achieve conventional 'Sliced' and 'Freeform' toolpaths. These all operate in full 6 degrees of freedom. All University models have the potential for programming via Open Platform third party software solutions. These include ROS Industrial and RoboDK software application. RoboDK costs for academic use make it a very feasible option. RoboDK also has a very good graphical simulation function allowing offline development work and also application to a wide range of robots and applications.

Fig. 119 Kuka KR6 Industrial Robot (Kuka uk)

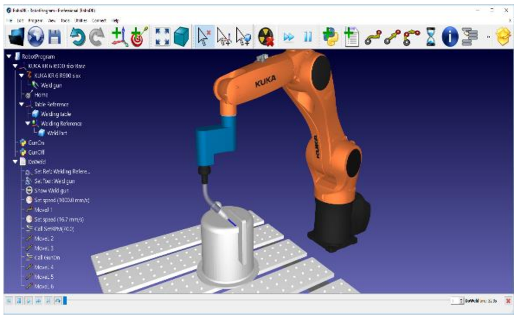


Fig. 120 RoboDK Screen capture of KR6 simulation (Fox.A,2020)

Fig. 121 Conventional 5 axis machining, extended to 3D FDM application Ethereal, India.

With the use of true three-dimensional toolpaths, the extrusion nozzle can trace the complex contours of a curved surface as opposed to using slicing to approximate them resulting in a stair stepped appearance. These applications need far more development work both on the geometry of the path and the nature of the equipment for successful part production. This type of application method would certainly reduce errors in the printed parts compared to the solid model.

The conversion of instructions to G-Code is beneficial as many Additive Manufacturing system controllers interpret G-Code. It may be beneficial in the future to develop controllers that recognise other interpolations above basic G0 and G1 F. The introduction and development of G2 and G3 circular interpolations and other geometries could be extremely beneficial in creating true 3D paths.

6.2 Summary

The requirement for support structures and post processing are obvious drawbacks to the AM process. However, with the application of Robot Based Additive Manufacturing there are far more opportunities for future research and development of alternative printing routines using additional axes and angles of print approach in relation to gravity. This research may also be enhanced by fast cure materials developments using temperature, daylight or UV curing approaches etc. These developments also have the potential to open up new print strategies which can move away from layering and start employing structural approaches such as Hamilton path printing etc.

The use of robot platforms also makes hybrid printing/machining applications far easier to configure & more viable for relatively lower cost products such as Furniture.

7 Chapter 7 Case Study Methodology for Environmental Analysis

7.1 Load and Force assumptions when creating the Generatively designed furniture chair products.

Prior to beginning to specify a generative study, it is essential to be clear about the nature of the loadings that will be specified for that structure. As AI will be creating the final structures this initial stage is critical in achieving a meaningful outcome. If the specified loads are too small the structures risk failing in service, however if the loads are too great the resultant iterations will be wasteful & 'over engineered'. The product policy may also impact the way in which these loads are quantified ie. 'Lifetime Guarantee' as opposed to planned failure after a given number of cycles etc.

The more information that can be identified, quantified and added to the model the greater the chance of producing an optimum solution. Often these loads are not as simple as they first appear and the designer must establish them through experimentation and simulation.

British standards guidelines for seating are established in the form of:

BS-EN 1022: 2018 Furniture – Seating – Determination of Stability (Global Seating Standard)

This new standard supersedes previously established standards such as:

- BS-EN 4875 -2 1985 Seating. Strengths and stability of furniture. Chairs/stools
- BS-EN 4875 -4 1985 Seating. Strength and stability of furniture. Settees.
- BS-EN 1022:1997 Seating. Domestic Furniture. Seating. Determination of stability.
- BS-EN 1022:2005 Seating. Domestic Furniture. Seating. Determination of stability.
- BS-EN 1335-3: 2009 Office Furniture, Office work Chair. Test Methods
- BS-EN 581-2:2015 Seating and tables for camping, domestic and contract use

Some of the key changes to the standards were:

- Introduction of a new test method to establish corner stability
- Introduction of a new test method for chairs with raised sides (not arms)

- Requirement for swivel seating requires a rearwards stability test of 130 kg (previously 110kg for domestic seating)

There are a number of categories that must be identified for inclusion, as appropriate, into the model as follows:

Static Loads, that are applied slowly and build up to their final value, while then remaining constant.

Repeated Loads, which are successively applied and removed from the structure for a considerable number of cycles. These forces may be responsible for fatigue failures at a much lower intensity than static loads.

Impact loads, applied suddenly by a body in motion in many instances. The effects of these impact loads are often more dramatic than those of static loads which are applied gently.

Location of the loads is of equal importance in the generative study as they may be either concentrated into a specific area or may be more general and distributed across the entire structure of the product.

Force assumptions regarding the product use are also necessary for meaningful results. These are the action of one body on another. These can be both contact and non-contact forces which attempt to change the shape of the object to which they are applied. These applied or contact forces are extremely common in Furniture in addition to the usual ambient non-contact forces such as gravity etc.

These forces can be further subdivided into **'internal'** and **'external'** forces. These are the subsequent forces which develop inside the structure in response to the external loads. These maybe also classified as applied or reactive forces.

The direction of loads and forces are also critical for the creation of a realistic production of a generative product. In essence there are six possible independent forces that could be applied to the body.

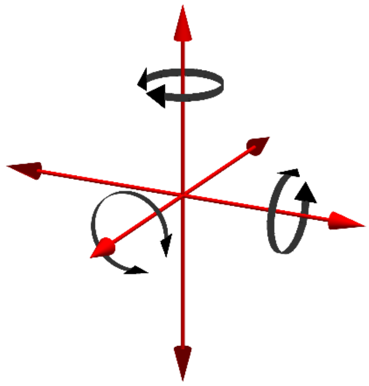


Fig. 122 Six Degrees of potential force directions and combinations

When two or more independent forces act on a body it is often more convenient to combine these into one single force which has the same effect.

When all forces are equal on a furniture body we can say that it is in equilibrium. These forces can be assessed initially using a simple free body diagram, this will produce a strategy for application to the generative study criterion for ‘support reaction’.

The definition and application of supports to the structure is an important consideration. In a simulated three dimensional environment there is the possibility of movement in six degrees of freedom when the structure is not constrained. In most cases some movement constraints exist for the structure. These structural constraints can be categorised into three main groupings:

- ‘Roller’, Allows both horizontal and rotational movement of the constrained elements. They therefore have five degrees of freedom and one degree of constraint.
- ‘Pinned’, Allows rotational movement in all axes but does not allow vertical or horizontal linear movements. It therefor has three degrees of freedom and three degrees of constraint.
- ‘Fixed’, will not allow horizontal, vertical or rotational movement. It is therefore fully constrained in all six degrees of freedom.

It is not always easy to illustrate a free body diagram correctly as the forces and their magnitudes and points of contact cannot be accurately determined.

7.2 General Design Considerations

It is essential when making specification decisions that a number of strategic outcomes are considered.

The usage classification of the product:

- Light duty Household
- Medium duty Household
- Heavy duty household or light duty institutional
- Medium duty Institutional
- Heavy duty Institutional

7.2.1 Chair seat loads methodology and assumptions.

- **Side Chair**, vertical seat loads for seating would be expected to be in the region of the users' body weight. In studies it has been established that the 95th percentile value of 98 kg and a 99th percentile value of 109 Kg is the range for a for a light clothed male subject. According to these figure no more than 5 % of the male population will weigh over 98 Kg and no more than 1 % will weigh over 109 Kg. These however must be tempered against rising weight trends in the population. The survey also established that 4% of office workers weighed over 181 Kg (Damon et Al 1966).

Dynamic loads must also be considered when assessing the load specifications of seating. It has been illustrated that in sitting and standing from a chair forcefully the load may be up to twice that of the static body weight. Therefore for the 99th percentile example the dynamic loading on the chair may be in the region of 227 Kg. In other tests using sand bags dropped from a 6 inch height onto the chair platform it has been shown that the load may be up to 7 times its own weight ie. A 136 Kg bag dropped from 6 inches may exert a momentary force of 952 Kg.

Having established the loads to be expected it is also of critical importance to assess in outline how one considers those forces are going to be transferred down through the structure of the chair.

Severe usage values for wooden contract seating could be in the region of 127 to 145 Kg (American Library Association 1983) Comparable values for Upholstered Seating being in the 136 – 181 Kg range.

Back loads, are applied to the chair back when the user sits in the chair and leans backwards. The load is related to body weight and studies of heavily loaded chair backs found that 102 kg man could exert a back force of 63.5 Kg (Hart 1967) Widely applied back forces vary from 41 Kg for medium duty domestic seating to 136 Kg for heavy usage institutional applications. It is also necessary to anticipate any abnormal usage of the furniture item, for example when a user sits on the back of the chair with their feet on the seat or when a user leans back onto the backfeet of the chair. These considerations could also include impact loads that may be encountered if the seat is tipped over due to relocation or misuse.

Torsional loads on a frame can occur when the seat is loaded and tilted backwards whilst being twisted from side to side. This has the potential to cause damage to the frame as out of plane bending forces are applied to the structure and its jointing. These forces should be in the region of 102 Nm while the chair is tilted back with a 79 Kg vertical force applied to it. To simulate the torsion of the frame the frame should be supported so that in affect the front legs are free.

Side Thrust Loads may occur when a person sits or rises from a chair they are likely to exert downward and outward forces to the arms. In a similar way if users choose to sit on the arms this must be accounted for in the design criterion. In tests it has been established that forces of up to 31 Kg can be exerted in this way by a person weighing 100 Kg. When these forces are applied the chair legs should be supported in a roller fashion to allow the frame to flex.

Front to back forces on the legs, are possible in scenario where the user stands behind the chair tilts it forwards and then leans heavily on the back rail. Children may also push heavily on the top rail in order to dislodge someone sitting in the chair.

- **Easy Chair**, this class of chair may experience increased loading during use due to persons sitting heavily into the chair and also persons sitting on each other's laps. This could equate to a man of 102 Kg sitting heavily into the Easy chair exerting a load of 205 Kg. It is recommended that cyclic loading of between 136 Kg to 200 Kg be applied to the testing of these chairs. Additionally due to their construction the heavy vertical loading will be transferred horizontally to other components through the suspension. This is difficult to measure but must be acknowledged. It is estimated that, taking the example of sinusoidal springs (zig-zag springs) that forces transferred to the rails by the vertical forces above could be as much as 68 Kg.

Maximum back loads of 45 Kg are common from testing with maximum loads of 75 Kg being recorded where abusive treatment of the furniture has occurred. The specification for Upholstered furniture calls for the cyclical loading from 34 Kg to a high value of 68 Kg.

Unlike the case of the side chair the Easy chair offers a comfortable seating option on the top of the arms so this becomes a consideration when looking at forces in its design. It seems logical that one would want to ensure that the arm structures could at least withstand the force of one seated user.

'Stretcher loads' can be encountered when the chair is used a step to reach objects just out of the reach of the user. It is recommended that the stretchers for testing should be able to withstand a vertical load of 102 Kg

This category of force is very much the same as that of the side chair values. Although there is less chance of the chairs being pulled sideways by the arms and more chance of users sitting on the upholstered arms. It is always necessary however to consider the style and type product construction when deciding the design loading parameters. The specifications for upholstered furniture specified the application of cyclic loading in the range of 34 to 91 Kg

- **Settee**, the vertical seat loads identified for a settee are of particular importance as they will determine the sectional requirements of the front and back rails in particular. This is not as straightforward as the decisions for the single chair as many loading scenarios exist for multiple user seating such as settees. i.e.
- Number of people
- Combined weights

- Abusive loadings
    - Sitting on another persons' lap when the settee is already full

Anthropometric data mixes also play an important part in the overall design strategy for multiple user seating, taking into consideration:

- Hip width
- Shoulder breadth
- Elbow to elbow width

It was established that a lightly clothed individual of approx. 104 Kg in weight, their shoulder width and elbow width dictated that the individual would require 53.3 cm of seating space. This when translate to the seat structure represents a loading of approx. 124 newton per cm.(48 cm is the minimum for an individual of this size to have reasonable comfort although sitting alternately to the front and back of the chair a minimum value of 17 inches is possible, but the comfort levels would be far lower.

The forces applied to the back of a settee one would expect to be similar to those applied to an Easy Chair. The schedule developed for the vertical seat loading should be equally suitable for application to the back forces.

Specifications call for the application of cyclic loads in the range of 34 Kg in light use to 68 Kg for heavy usage acceptance. The loads should be applied in the centre of the top at each sitting position.

The positioning & Location of vertical seat loads on the model is also of great importance especially when allocating loads in the generative environment as it will have a very direct and significant influence on the creation of the iterations structure. In a traditional construction it will dictate how much weight is borne by the front and back rails. In the generative design it will have a significant influence over the preservation and erosion of material throughout the structure.

The following figure below shows the front to back weight distribution during the study on a car seat. These results will be influenced by the rake and seat angles so should only be taken as an illustration.

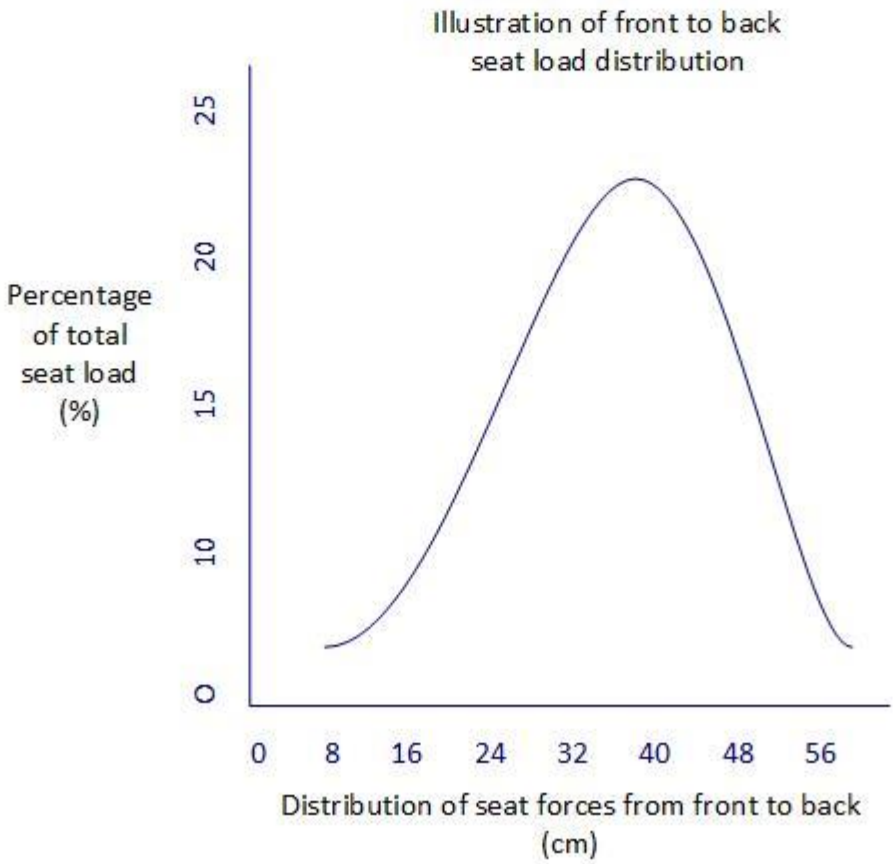


Fig. 123 Illustration of seat load front to back (Lay, Fischer et al., 1940)

The study illustrated that the resultant of the load carried by the seat were 56% of the distance from the front to the back of the seat.

7.3 Case Study Environmental Analysis

7.3.1 Life Cycle Analysis structure and standards methodology

Definition. *'The ISO 14040/44 standard defines a Life Cycle Analysis as a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its lifecycle'.*

There are 4 clear steps to most Life Cycle Analysis studies:

- **Step 1:** Define the goal and scope of the LCA Study
- **Step 2:** Make a model of the product life cycle
- Life cycle inventory (LCI) : With all environmental inputs and outputs
- **Step 3:** Understand the environmental relevance of the above Life Cycle Inventory
- **Step 4:** Interpretation of the Study

There are a number of ISO standards that should be adhered to in the generation of the LCA study to ensure consistency and comparability of the results.

- **ISO 14040**

  Specifies the framework and principles of an LCA study

- **ISO 14041**

  Details the requirements and guidelines for the study

- **ISO 14067** Greenhouse Gas Protocol (GHG)

  Greenhouse gas emissions of products

- **ISO 14046** Water Footprints of products, processes & organisations

For Reference to Supporting specifications regarding the correct design and options for creating a Life Cycle Analysis see

APPENDIX D

D.1 Product Category Rules & Environmental Product Declarations

D.2 Approaches to Goal and scope definition

D.3 Methodology for the use of foreground and background Data

D.4 Framework for widening the scope of sustainability

D.5 Impacts of ISO on assessment methodology

D.6 Selecting a method

D.7 Normalisation

D.8 Weighting

D.9 Interpretation

7.4 Case study specific 'Ecochain Mobius' modelling approach

The case study utilises a Dutch commercial LCA software platform named Ecochain Mobius. It was selected from a number of rival platforms including Simapro which has more of an organisational focus. Mobius is very much a product focused LCA application which is ideal for this particular type of product footprint analysis. Mobius does however consider a number of discrete levels within the LCA analysis, which are as follows:

- Company analysis
- Process analysis
- Product analysis

The three levels of LCA data input encompass the following:

On this level one can add usages and emissions data, using this organizational summary to allocate environmental contributors proportionately to the individual products.

- Energy usage
- Business transport
- Process emissions
- Direct natural resource usage
- Supplier profiles and materials
- Supplier transport distances

At the ‘Process Input Level’ of the model the allocation of energy and emissions at company level takes place. The company wide summary can be broken down in order to identify the specific contribution of each process used to produce the products.

- Comprehensive List of Processes
- Energy use & emissions of each process

At the ‘Product Level’ the analyst allocates processes and materials to individual products.

- Estimated/historical production volume
- Bill of Materials (BOM)
- Process usage for the specific product

7.4.1 Methodology for the LCA Product Structure and Life Cycle

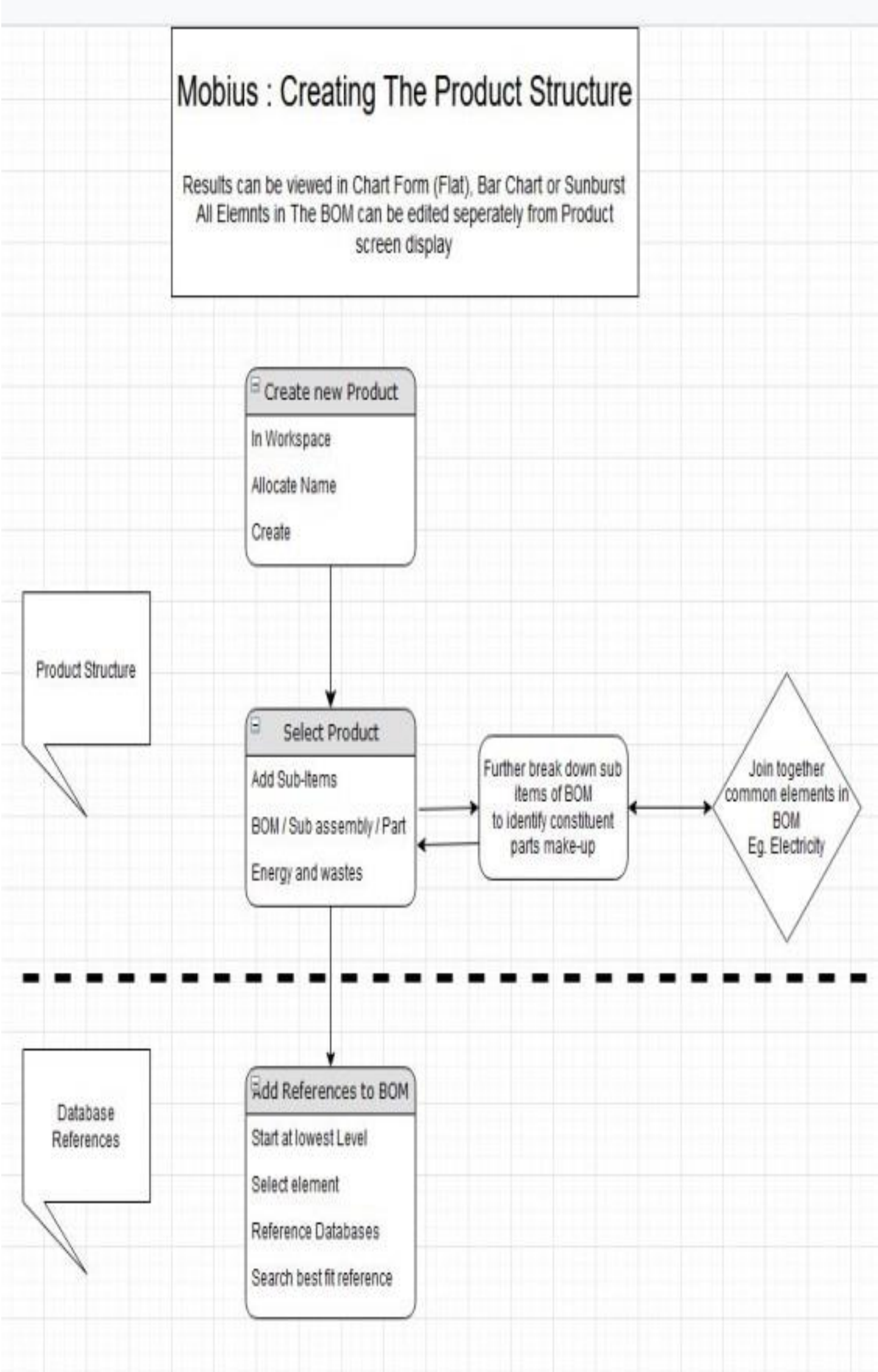


Fig. 124 Mobius: Flow diagram to illustrate Phases in the creation of a product structure (Fox.A, 2022)

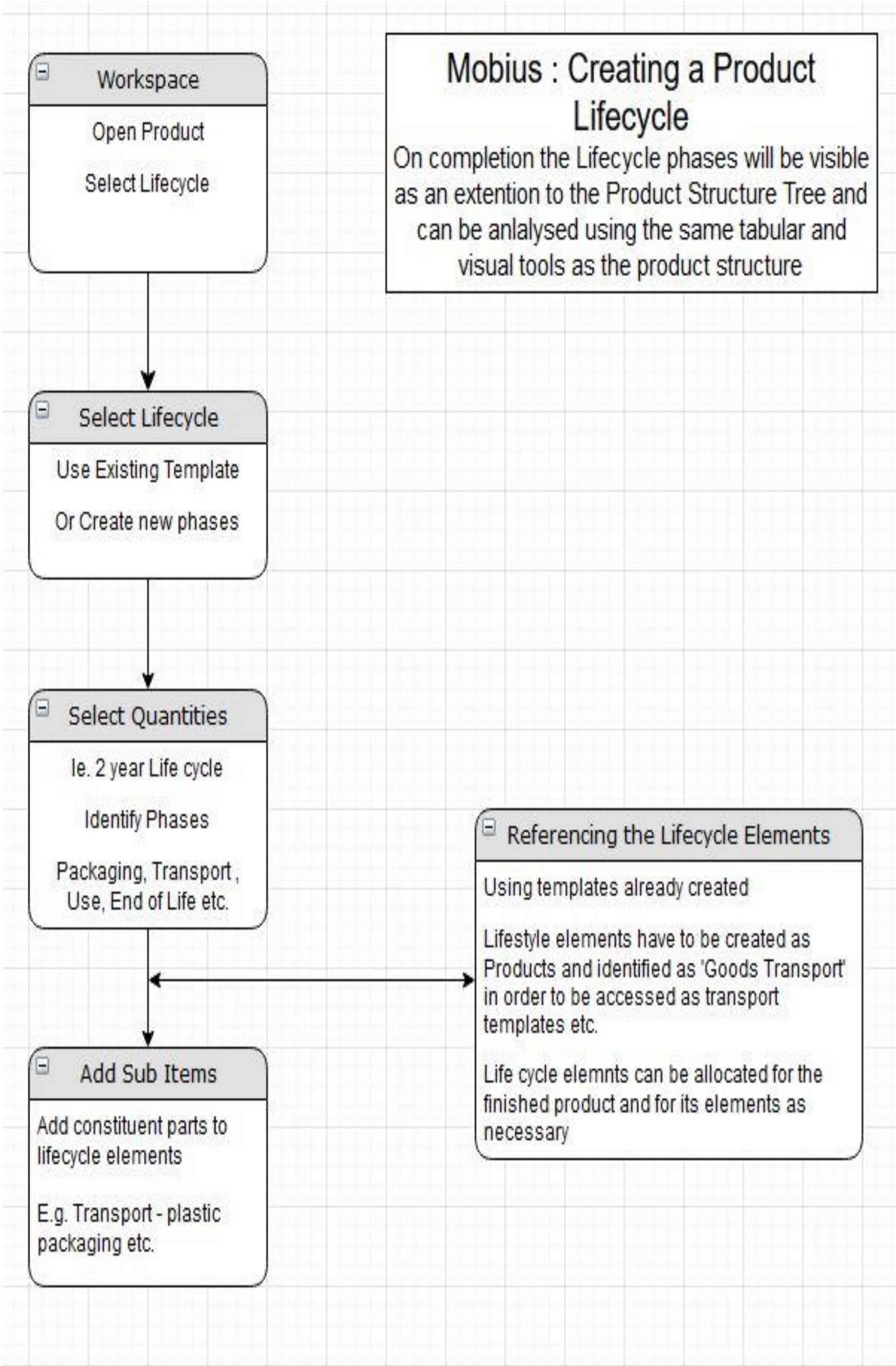


Fig. 125 Mobius: Flow of Phases to create a Product Lifecycle (Fox.A,2022)

7.4.2 Product Scenarios

In addition to these three levels of data Mobius enables the analyst to create different product usage and end of life strategies which will potentially affect the environmental footprints of the products. These scenarios help the organization to assess their Corporate Strategies for a successful implementation and positive contributions to the circular manufacturing economy.

Material, process and energy data at the distinct levels is obtained initially through selection of appropriate EcoInvent databases for the specific products and processes being performed. It is possible to also interrogate other commercial data bases or if required use primary historical data collected by the organization. The use of primary data obviously makes the final analysis far more specific and focused to the organizations' activities and products. One of the main challenges when using third party databases is to establish the most appropriate database reference in order to create realistic profiles.

The outcomes form the LCA analyses can of course form the foundation for creation of publically available and downloadable Environmental Product Declarations (EPD). EPDs take account of the products' performance over its entire lifecycle, from materials extraction, through product manufacturing, its usage stages and eventually its end-of-life scenario. These are independently verified for application conformity & logged in databases such as International EPD System. As such the EPD's are compliant with ISO 14025 directives. Contrary to myth these EPD's do not contain sensitive commercial details but do give good comparable information for comparing environmental performance within the same product grouping.

7.4.3 Comparative Life Cycle Assessment of AM Vs. Traditional Methods

The subject of the case study is an original design named the ST1 Chair manufactured from Tubular Steel and Laminated European beech profiled panels. This design base was chosen as it is a modern product concept which is capable of being manufactured using both traditional and modern wood and metal manufacturing processes.
It presents a challenging and demanding geometry for the generative design application to demonstrate geometry tangible improvements in form and material utilisation.

This is compared to a GTX1 Chair product designed wholly using generative design methodology and manufactured using Robot Based Additive Manufacturing technologies.
Although not identical they are similar enough in form and function to give a meaningful estimate of the benefits and drawbacks of each methodology.
It should be borne in mind that any case study of this nature undertaken outside of an established organisation is at best an educated estimation of overall benefits and drawbacks. Without sources of primary data the choice of secondary data from a selection of databases is by its very nature open to different interpretations and hence selections.

7.4.4 Outline of scope and parameters

The aim of the case study is to demonstrate the differences that exist between current manufacturing methodologies (i.e., including the use of CNC machining and robot technologies) with the proposed future Robot Based Additive Manufacturing scenario. The areas that will be examined are as follows:

- The capital equipment base required to achieve each of the products being compared
- The time taken to produce the products together with the potential for mixed product production
- The effect of the methods on the Bill of Materials (BOM)

- Throughput considerations when manufacturing multiple products
- The Life Cycle Analysis (LCA) profile associated with each approach to manufacturing and hence their relative advantages and disadvantages for the development of a 'Net Zero' Circular Economy in the Furniture Sector.

The scope will be limited to the comparison of two products, one made traditionally from timber and steel, compared to a polymer product made using robot based additive manufacturing (RBAM). In the case of the LCA study, the analysis will be limited to secondary processing and logistics due to time constraints. In reality the LCA would also consider the primary processes involved in the extraction and processing of raw materials together with their logistics to the wholesale market. Although limited, this should still give a representative comparison of the two products and their manufacturing methods.

7.4.5 **The model for analysis, Traditional.**

Fig. 126 The Traditionally Designed 'Ripple Chair ST1' (Fox. A, 2022)

The traditional product designed using Solidworks and fusion 360 is a typical tubular steel framed occasional chair utilising 24mm x 10mm (1.02mm thickness) oval sectional frame weld at the joints. The seating and arm rests are constructed from circa. 15mm European Beech Laminate with two cross laminar elements to maintain the stability of the final sub assembly. These veneer laminations once machined are attached to the steel square section cross frames using mechanical threaded bolt fixtures. Although the frames are manufacturer in a traditional methodology, they do employ robot welding and spraying in their construction and also Radio Frequency curing is used to speed the throughput of laminates from lay-up to final curing of the Urea Formaldehyde adhesive.

7.4.6 Component routings and Standard Times for the traditional chair design & manufacture

The laminations as previously mentioned are a final thickness of 15mm and are constructed using 2 cross laminations and an odd total number of laminates to maintain stability. The construction process employs Radio Frequency curing in a matched mould to give the necessary form to the final sub-assemblies. Final Shaping and profiling are achieved employing a 5 axis CNC router with ATC to give the final profile together with the edge softening profiles. This type of machining is necessary due to the three-dimensional nature of the laminations and the necessity to keep tooling at a constant perpendicular pitch to the surface in order to maintain the profile and to avoid breakout of the laminations. The final laminations are finished using an extremely hard wearing two-pack industrial polyurethane spray lacquer. (It is applied by robot to avoid the prohibitive Health and Safety issues and costs of humans spraying polyurethane. (Isocyanate catalyst is carcinogenic and requires independent air fed masks)).

Machine-Centre numbers for manufacturing the chair for reference:

001 Veneer Guillotine
002 Veneer Stitcher
003 Mechanical Adhesive Mixer
004 Double/Single Sided Powered Glue Roller
005 Radio frequency Press Jig
006 Radio Frequency Press/Generator
007 CNC 5 Axis Router
008 Open Drum Sander/Brush
009 Metal Cut-Off Saw
010 CNC Tube Bender
011 Metal Twin Cut Off Saw
012 Linisher
013 Robot External Axes Welding Jig
014 KUKA Robot (TIG Welding Tool), KUKA Robot (powder coating head)
015 Degreaser/Condenser Line
016 Powder Coating / Heating line
017 Multi Spindle Borer
018 KUKA Robot (High Volume Low Pressure (HVLP) Spray Head and Compressor)
019 Infrared force drying tunnel
020 Brush final de-nibbing unit
021 Printing KUKA robot equipped with screw fed extruder and heated build platform
022 Solvent dip bath for support material removal
023 De-nibbing and sanding vacuum extraction bench

The total manufacturing time estimation taken from historical data records from Parker Knoll Furniture MRP II system which were established and implemented by me using Maynards Organisational Statistical Technique (MOST) which is a derivative system developed using data from the original MTM (Maynards Time Measurement) data traditionally used for directly observed work measurement and the setting of standards.

MINI MOST, MOST & MAXI MOST do not require the direct observation of the operations but instead work on averaged work content for ranges of motions or broader operations. As with all estimated work content these figures only give a broad indication of the actual work content. All the basic times are produced from 'dayrate' figures (i.e.75 BSi rating) to 100 BSi rated standard time and include a setup contribution per part. In addition to this the times are increased to take account of an industry standard rest allowance of 12% for environments which are noisy and challenging for the operatives during the working day.

The structure of the Bill of Materials can be seen below, for reference to the Manufacturing Routings and Standard times which were used to construct the final manufacturing times for the products see APPENDIX B.

Fig. 127 Arm Rest ST1/004 Bill of Materials (Fox.A,2022) (Routings Appendix B.1)

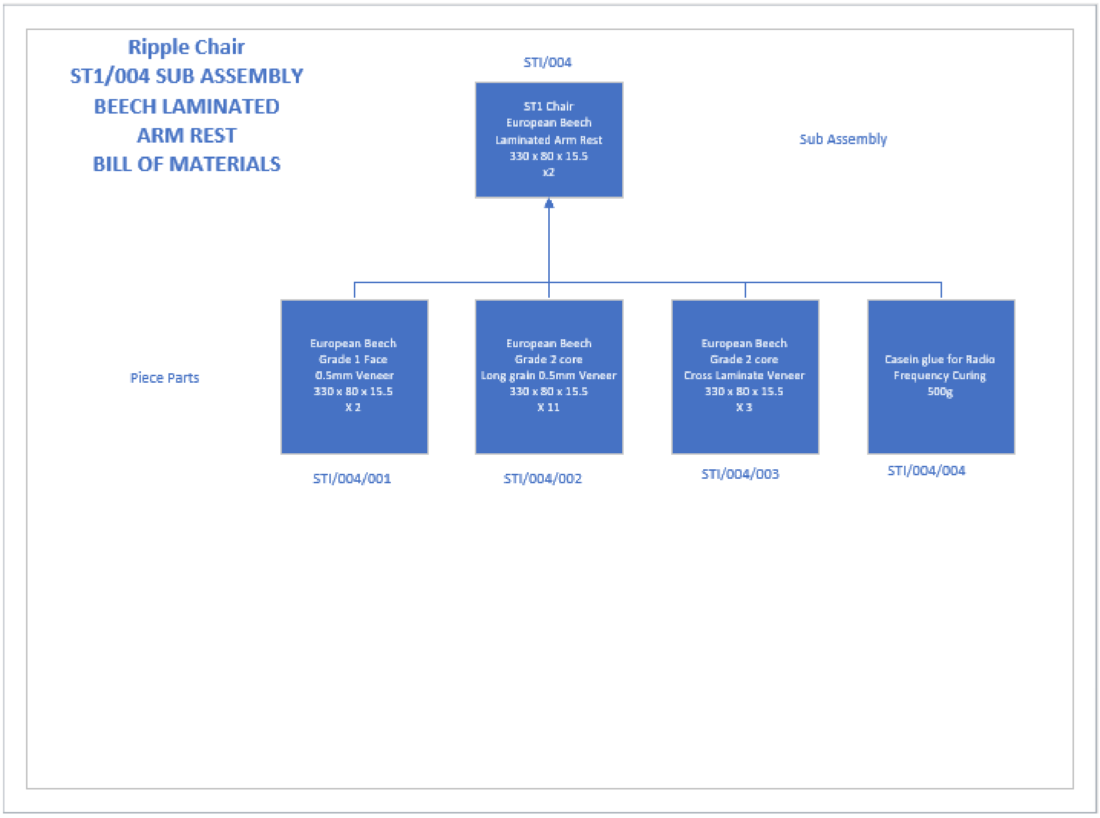


Fig. 128 Back Support ST1/002 Bill of Materials (Fox.A,2022)

(Routings Appendix B.2)

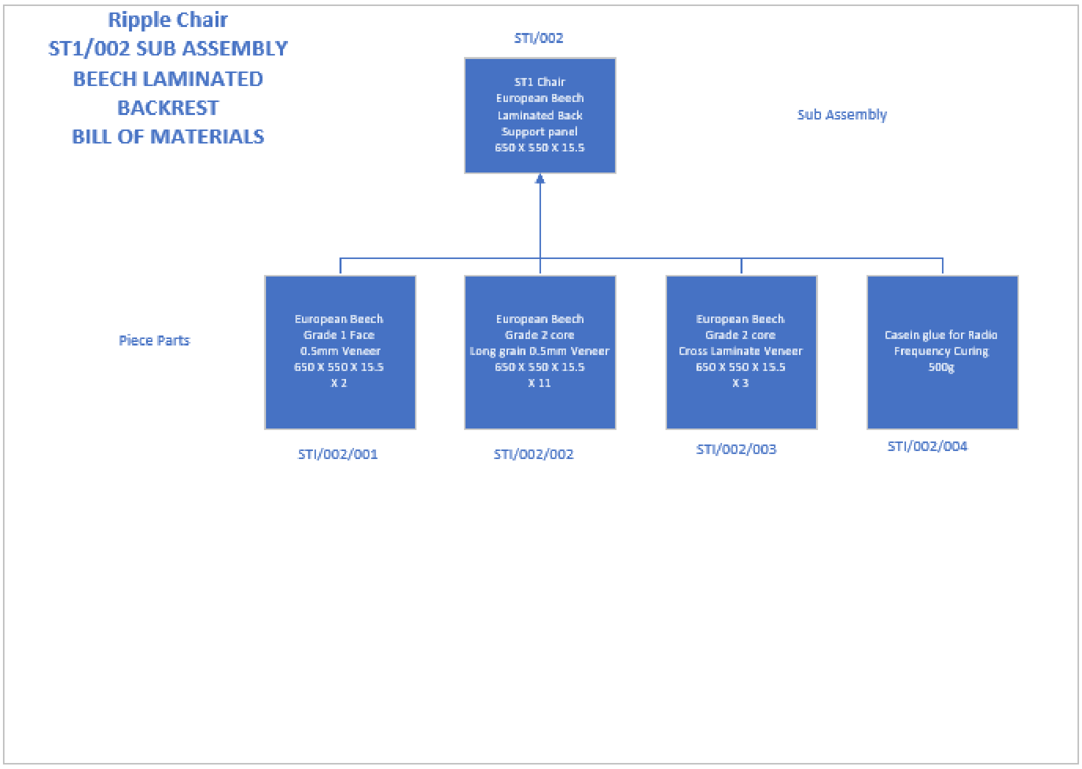
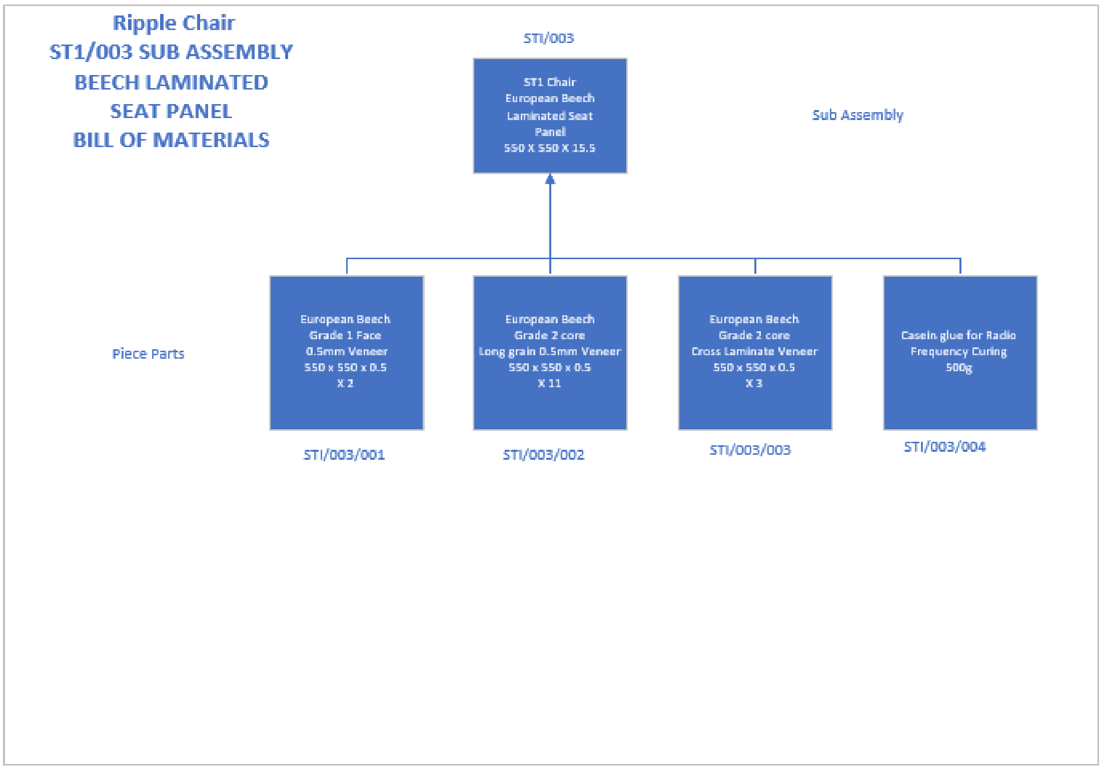


Fig. 129 Seat Panel ST1/003 Bill of Materials (Fox.A,2022)

(Routings Appendix B.3)



Steel Component and sub assembly routings and standard times

Fig. 130 Left Hand Side Frame ST1/001LH Bill of Materials(Fox.A,2022)

(Routings Appendix B.4)

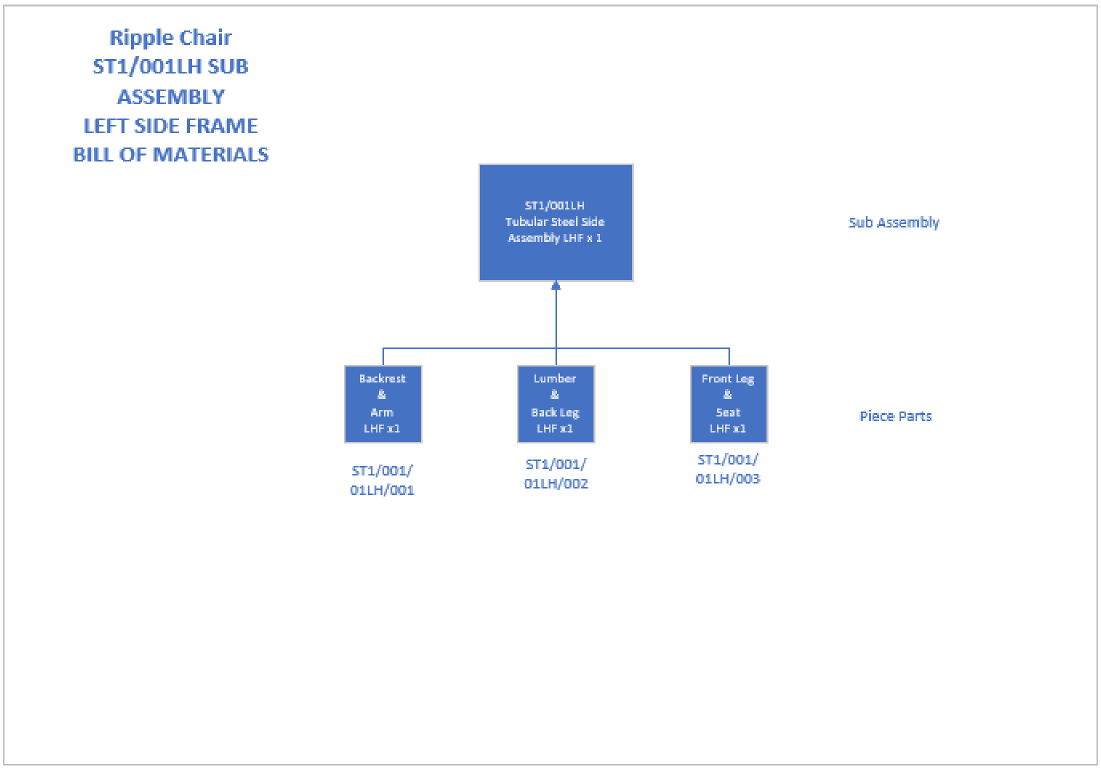


Fig. 131 Right Hand Side Frame ST1/001RH Bill of Materials (Fox.A,2022)

(Routings Appendix B.5)

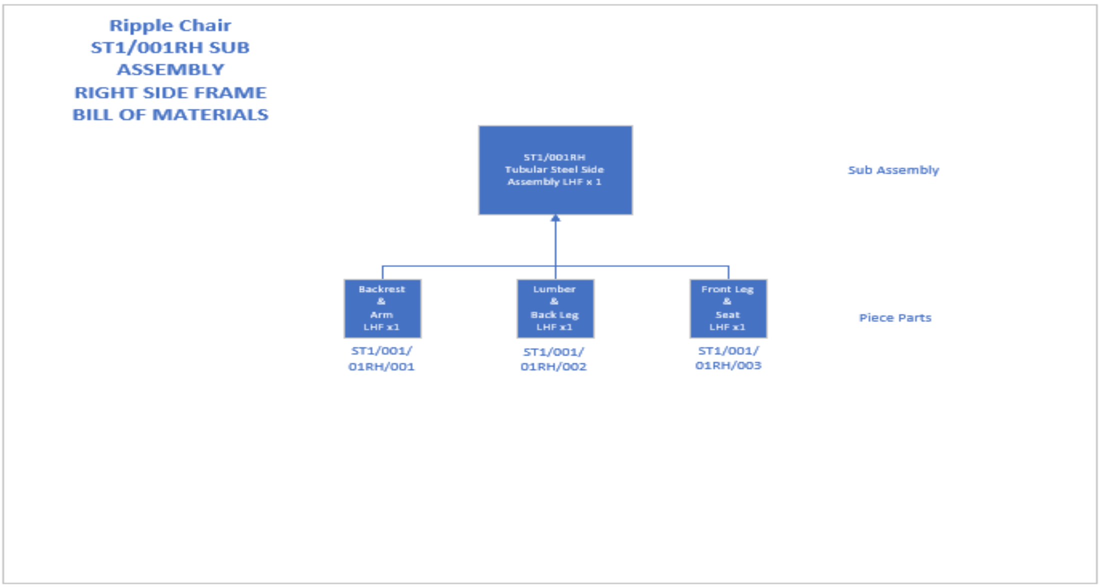
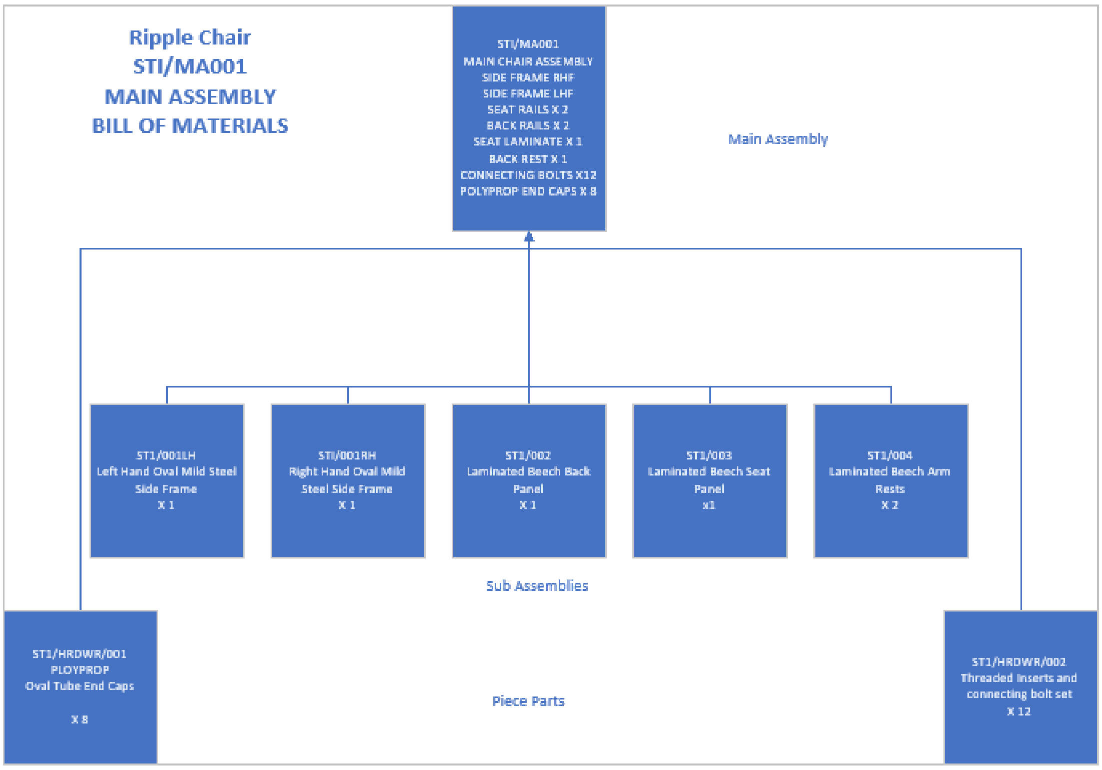


Fig. 132 Main Assembly ST1/MA001 Bill of Materials (Fox.A,2022)

(Routings Appendix B.9 (Also B.6, B.7 & B.8))



The total Manufacturing time per unit for the ST1 Chair is estimated at 531 standard minutes or 8.85 standard hours. Please note Standard Times are not pure time measurements but must be regarded as work content measurements for Payment by Results (PBR) or Manufacturing / Enterprise Resource planning schedules (MRP II / ERP)

7.4.7 The generatively Designed GTX1 Generation X Chair for analysis

The Generation X Chair is designed using Autodesk Fusion 360 based upon basic load carrying surfaces being identified and having appropriate load and pressure factors applied as outlined previously. Following this the constraints to the growth of the chair are applied and the software generates a number of iterations using cloud computing capacity. On average this process takes between 2 and 5 hours depending on the complexity of the structures, load characteristics and constraints.

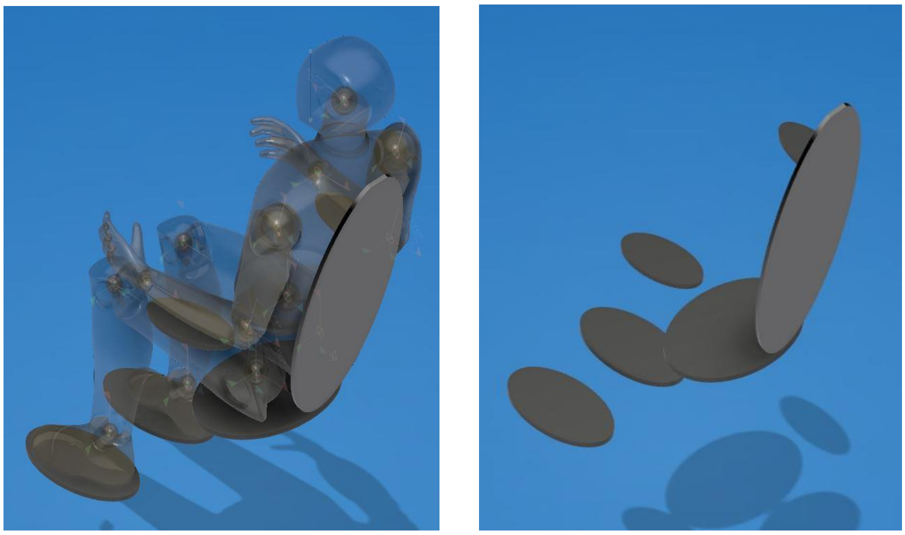
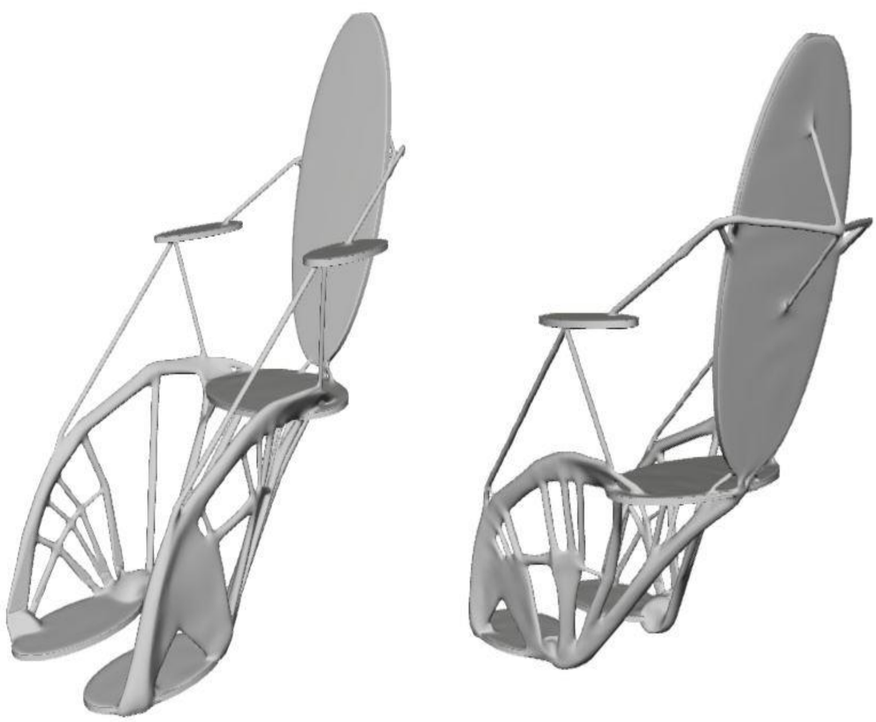
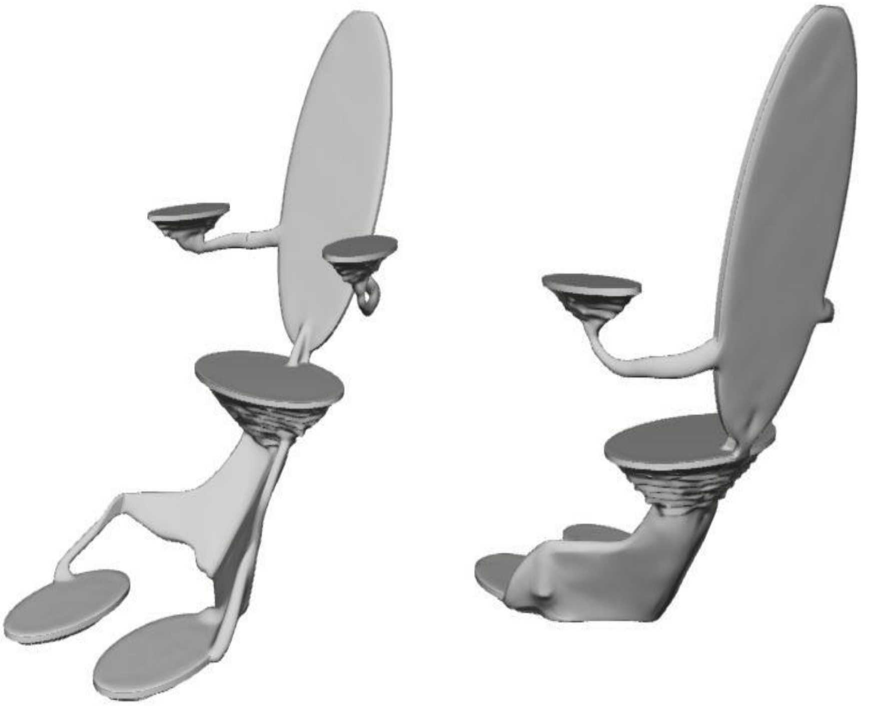


Fig. 133 Adjustable Virtual Mannequin used for positioning of the surfaces to support the body effectively, Fusion 360. (Fox.A,2022)

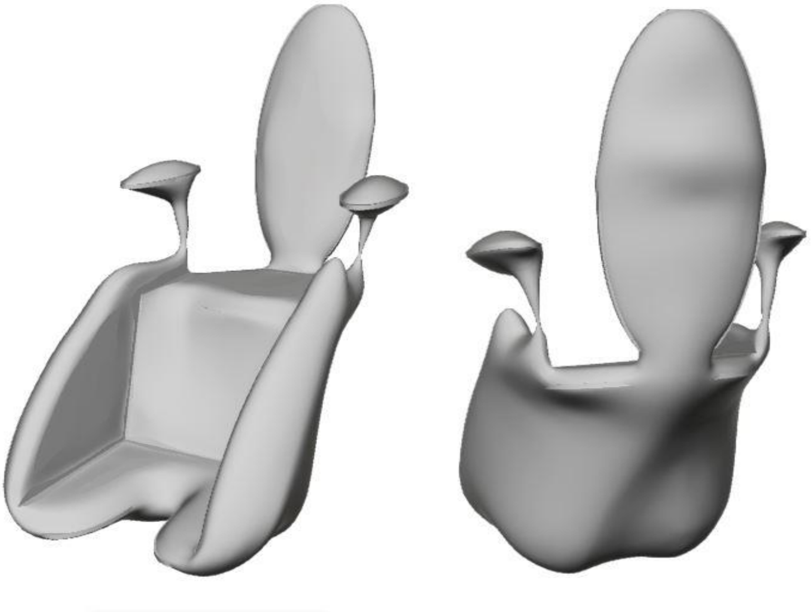
7.4.8 Examples illustrating the most promising Generative Iterations



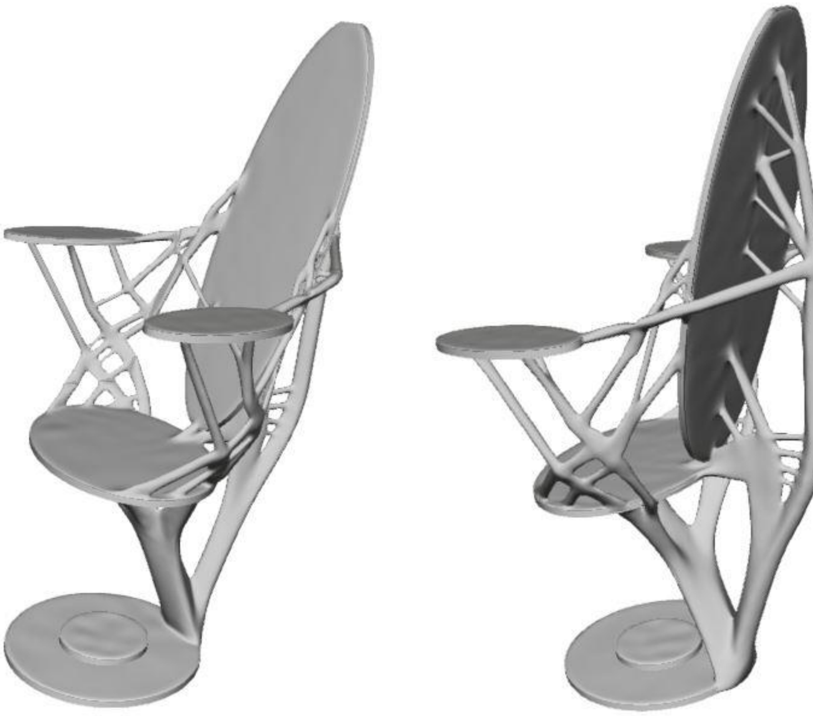
Iteration #1



Iteration #2

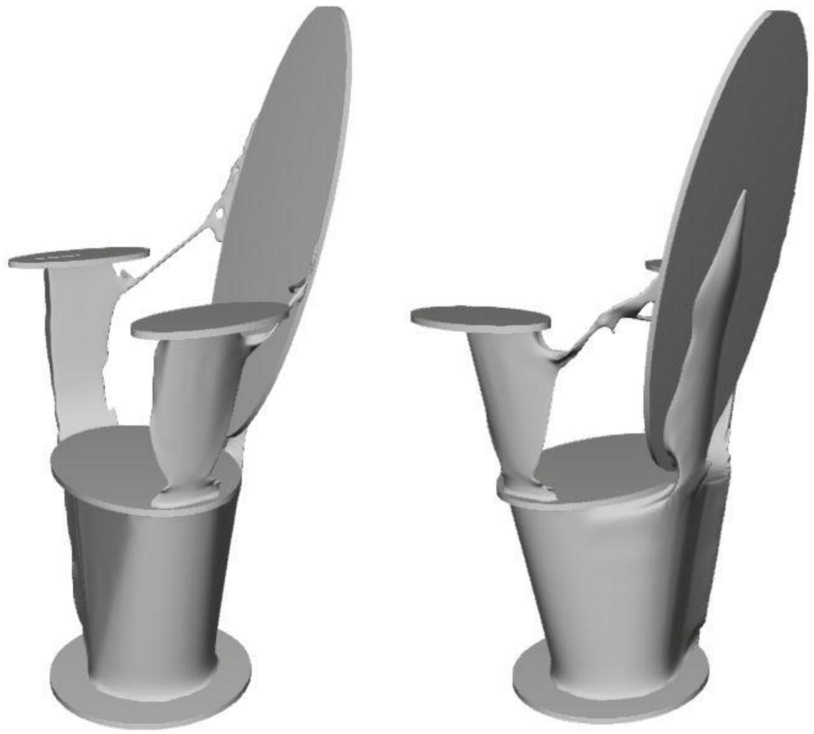


Iteration #3

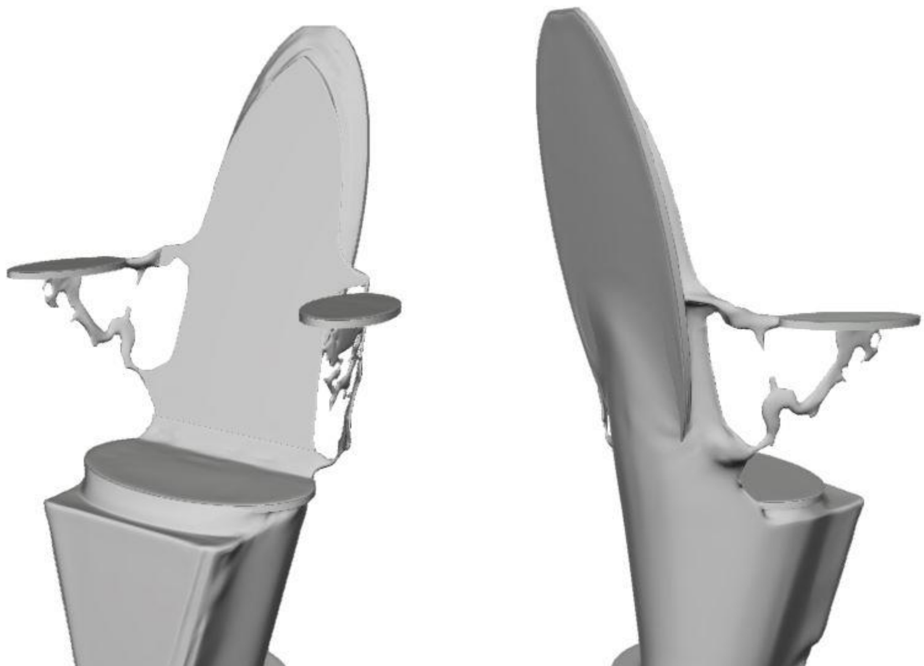


Iteration #4

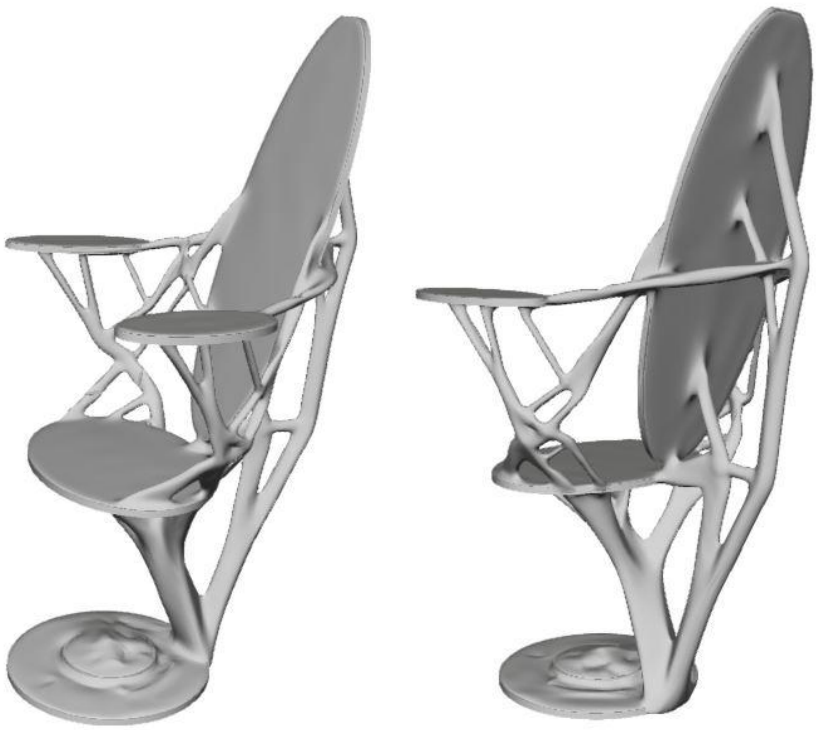
Iteration #5



Iteration #6



Iteration #7



Iteration #8

Fig. 134 8 No. iterations produced during the case generative study (Fox.A,2022)

Routing of the Flat Bill of Materials for the Generative TX chair frame

Main-assembly Routing

Handed: N   Main Assembly description: Generation X Printed Chair Frame

Model Name: Generation TX   Model No. : GTX1   Assembly No. : GTX1/MA001

Sub-Assembly/Part Nar	Part No.	No. off	eration sequen	MC No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Chair Frame for Robot Bas Additive Manufacturing	GTX/MA001	1	1	021	P/KUKA	Load Sliced Print design model to ROBOD workcell, heat print platten and commence Chair and support printing	7	601	608
			2	022	Dip Bath	Dissolve support structure in solvent bath	4	300	304
			3	023	Denib	Denib small blemishes and inclusions etc ready for spray painting	4	60	64
			4	014	S/KUKA	Apply polymer self levelling primer filler and warm air force dry	6	9	15
			5	014	S/KUKA	Apply polymer decorative surface finish clients specification and warm air force dry	6	12	18
						Component Part Totals			1009

Fig. 135 GTX Flat Bill of Materials (Fox.A,2022)

Iteration #8 was chosen by the designer for processing due to its form and aesthetic qualities together with the results of the generative design analysis that accompanied that iteration. The overall manufacturing time per unit for this iteration (at full scale) is estimated by Cura to be 601 minutes which represents a pure print time for the structure and supports of 10.01 hours. Inherent in this processing time is a contribution of 7 minutes towards the setup, maintenance and warmup of the build platform at the start/end of the processing run. It should also be noted that the time for this processing is less the 12% rest allowance requirement normal with manual production methods due to the automated queuing and execution of jobs without input from the human personnel (Apart from the offload and cleaning of equipment prior to the next build).

7.4.9 Analysis of the designs

The use of the integrated analysis tools of the generative design platform allows the designer to get additional information over and above the purely aesthetic assessment of the product iterations. These tools allow the designer also to make adjustments e.g. make the design symmetrical and then easily reassess the subsequent outcomes.

Using the introduction of filters to the generative process one can enhance the Designers ability to assess the suitability of the iterations produced. In the comparative diagram below one can see the results of merged generative studies creating a large number of iterations with slightly varying parameters. The multiple results in this case are then compared for volume of material used against the visual similarity. This helps to classify the iterations into 6 groupings from which individual designs can be selected for post processing e.g. manipulation for symmetry etc. The iterations in these cases were constructed by employing parameters that included a matrixed interior structure to reduce the mass of the final design. These sorts of parameters can be adjusted to give several comparative results from which final designs can be selected and further analysed, as we can see in the examples to follow.

The comparison below shows an unrestricted comparison of all iterations showing grouping for visual similarity.

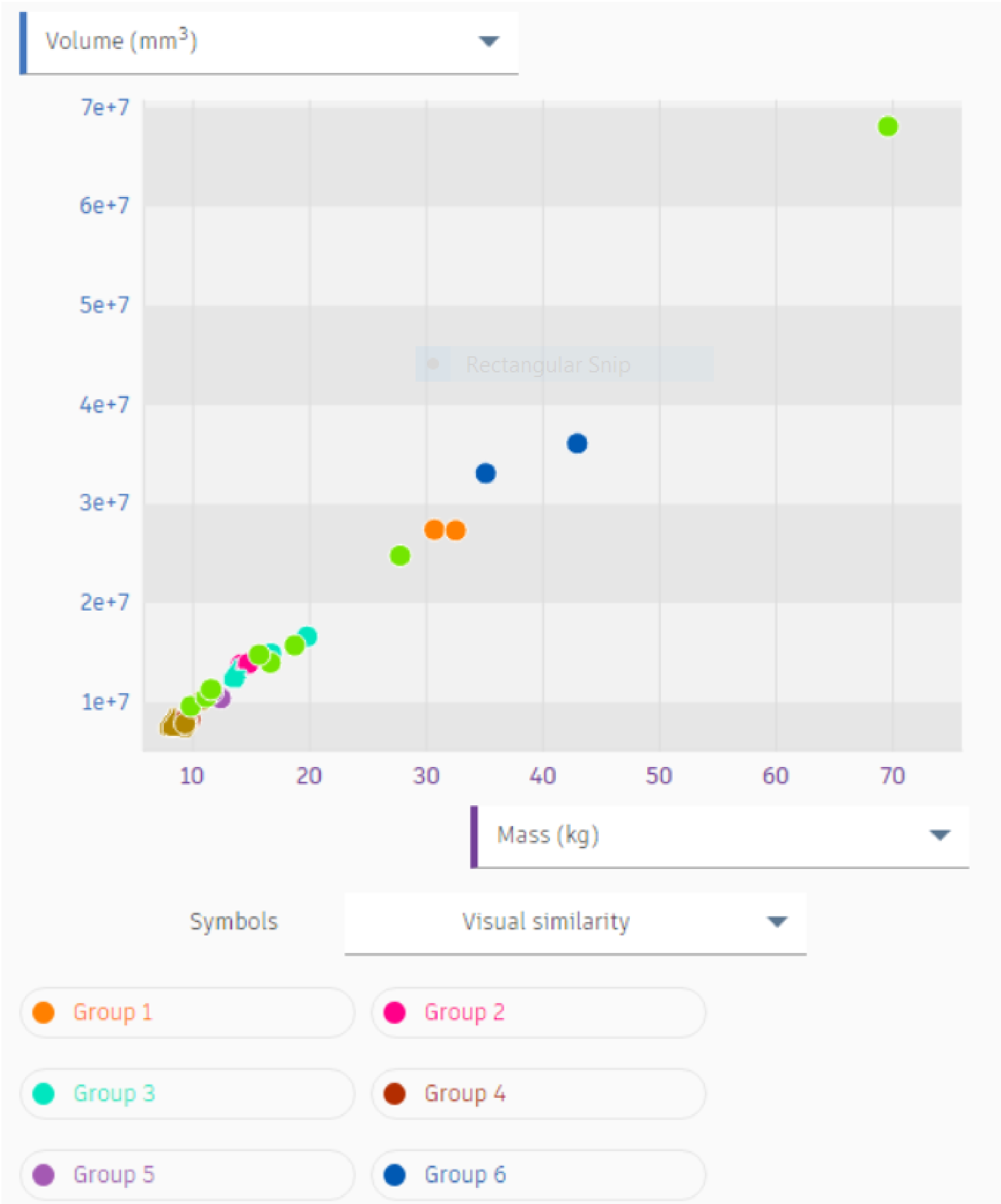


Fig. 136 Unrestricted Visual Similarity of the iterations produced by Fusion 360 (Fox.A,2022)

Fig. 137 Filters to narrow results to iterations of interest, Fusion 360

The table above in Fusion 360 allows one to adjust the ranges of a number of parameters to narrow the field of iterations being considered. It can include or exclude some selected studies together with other considerations such as materials, manufacturing methods, aesthetic qualities and the general parameters for volume, mass, stress analysis, factor of safety considered appropriate for the class and type of product being manufactured (at a level suitable for the health and safety legislation around that family of products).

One can see the result of restricting selected parameters on the number of acceptable iterations, in this case by limiting volume, Mass, Structural Stress Analysis, Factors of

Safety and Structural Displacement under load. The field is reduced to three iterations from a total output in excess of 25 iterations.
After narrowing of the field of iterations with overall editing of the global parameters the Designer can then further analyse the remaining iterations by selecting any combination of parameters for comparison. Once selected and displayed the resultant graphics are interactive with the numerical output attached to individual iterations available alongside by highlighting the iteration on the graph.

If a far more in-depth study is required within the envelope of an established organisation, the cost factors associated with the product can be introduced to the model allowing direct piece part and overall cost to be included in the comparative mix.

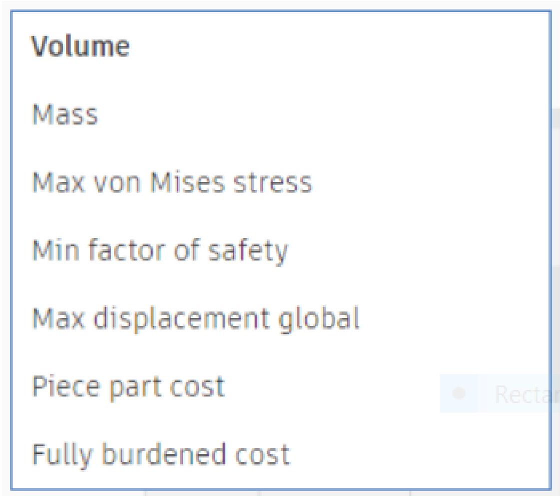
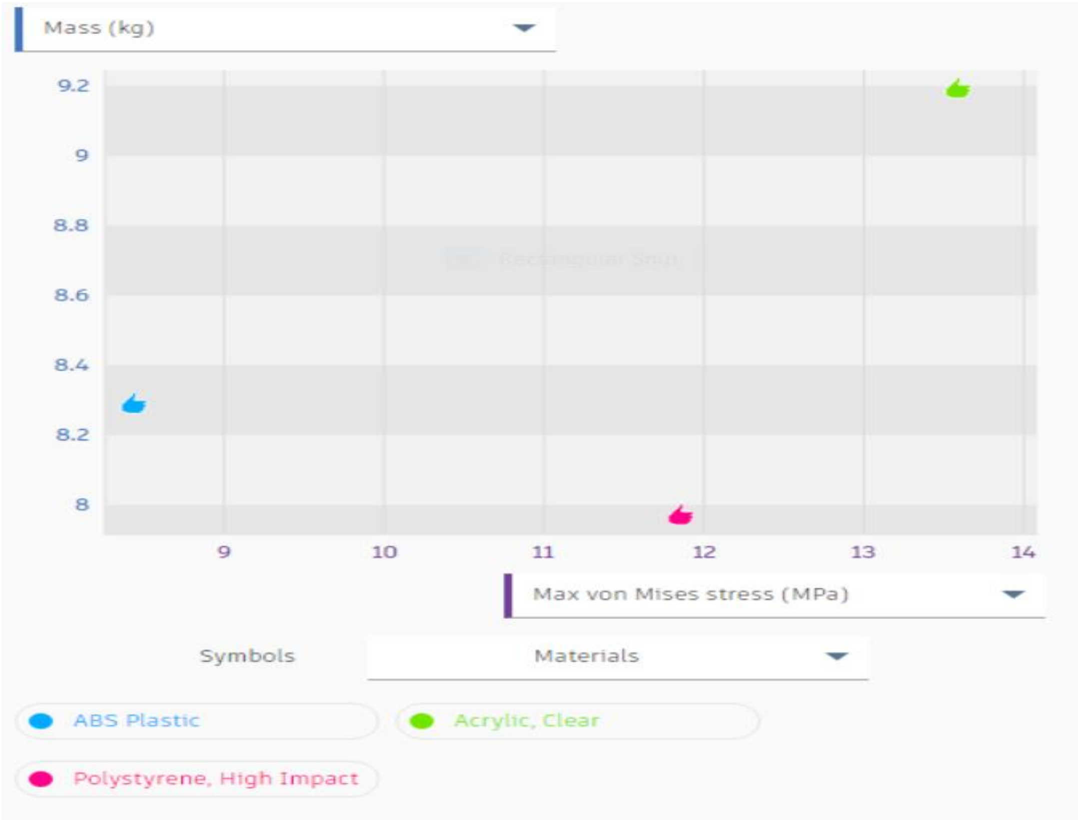


Fig. 138 Factors for comparison on Fusion 360

Mass



Von Mises Stress

Fig. 139 Materials Comparison: Volume Vs. Von Mises Stress (Fox.A,2022)

(For additional comparison examples see APPENDIX C)

7.5 Ecochain Mobius Product Analysis and Lifecycle Summaries

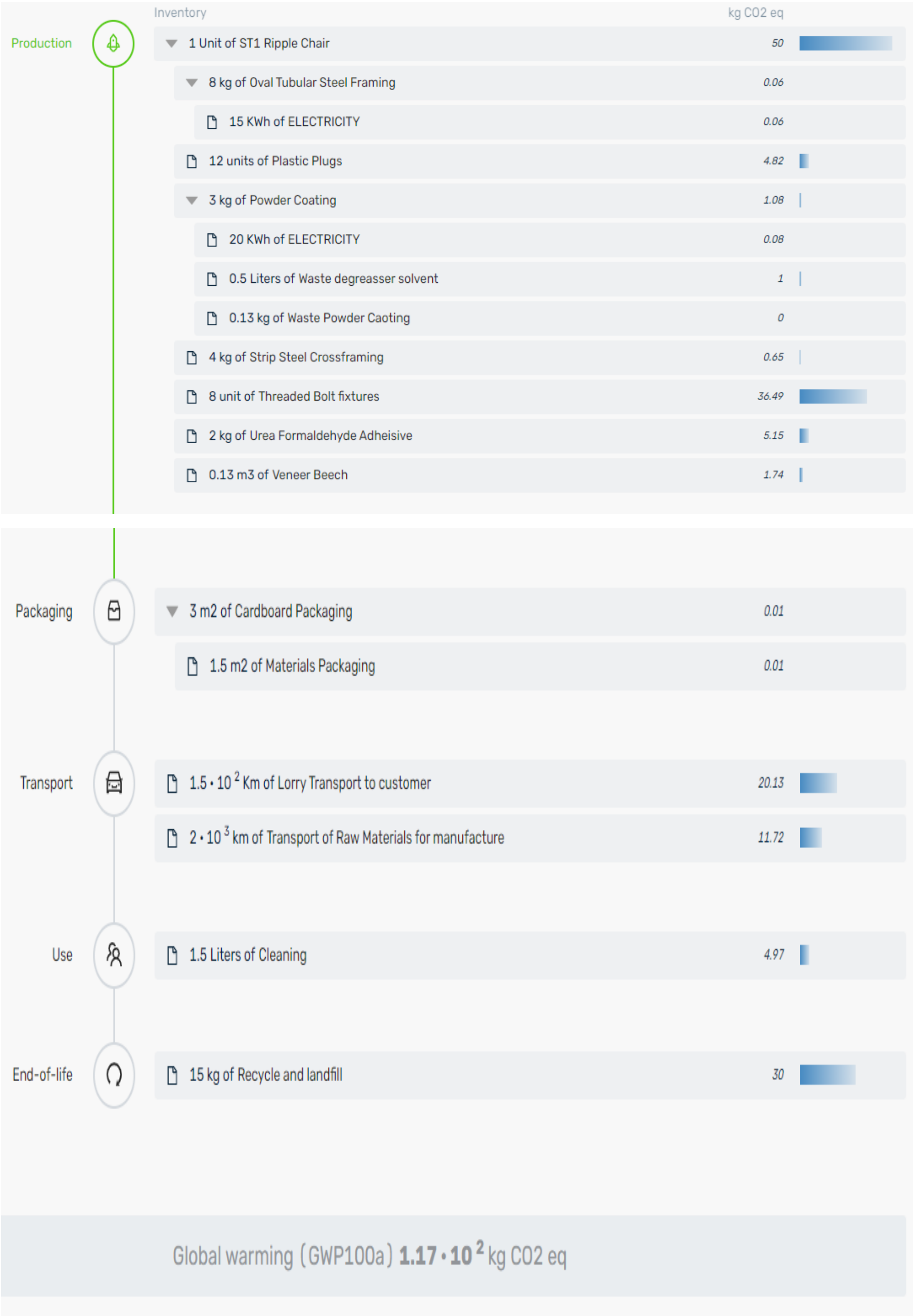


Fig. 140 Top Level summary of STI Ripple Chair Product and Lifecycle Analysis (Fox.A,2022)

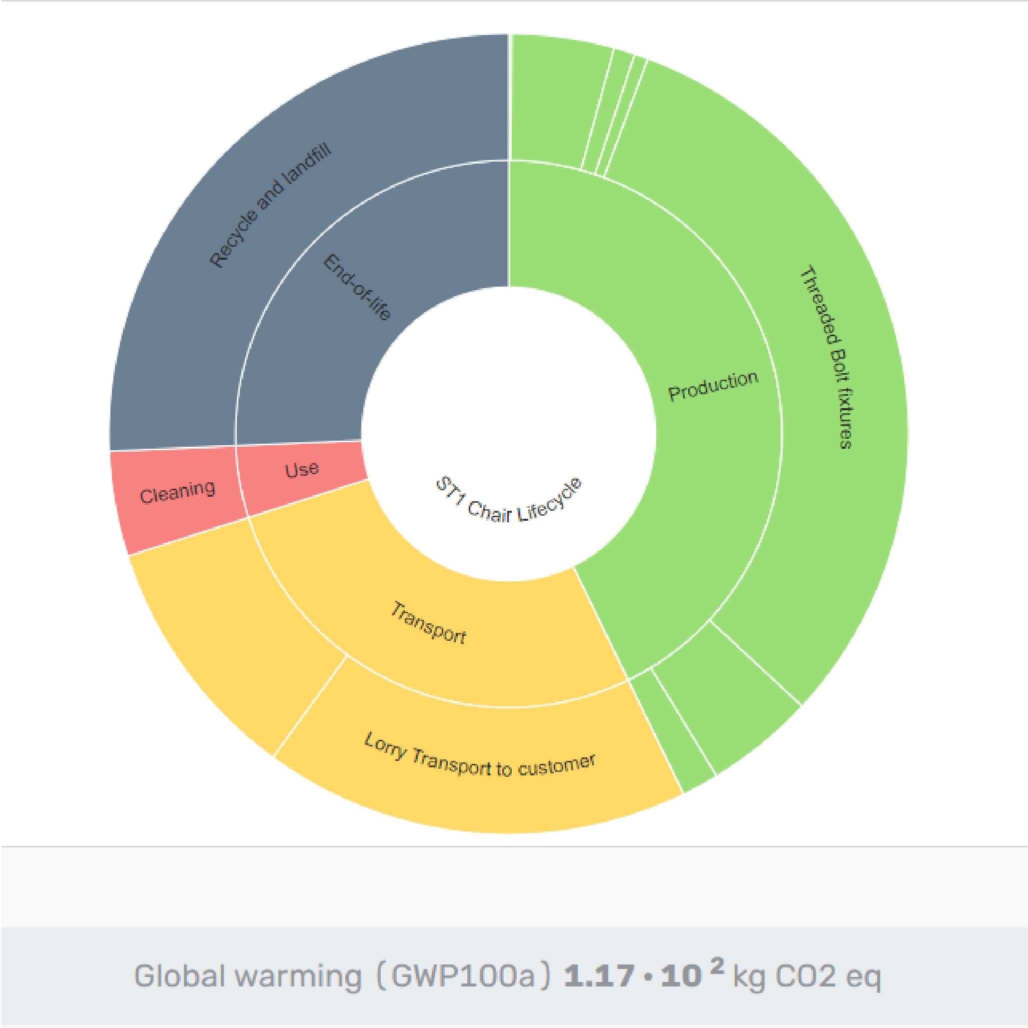


Fig. 141 Sunburst Diagram of relative elements in the ST1 Ripple Chair Product and Life Cycle (Fox.A,2022)

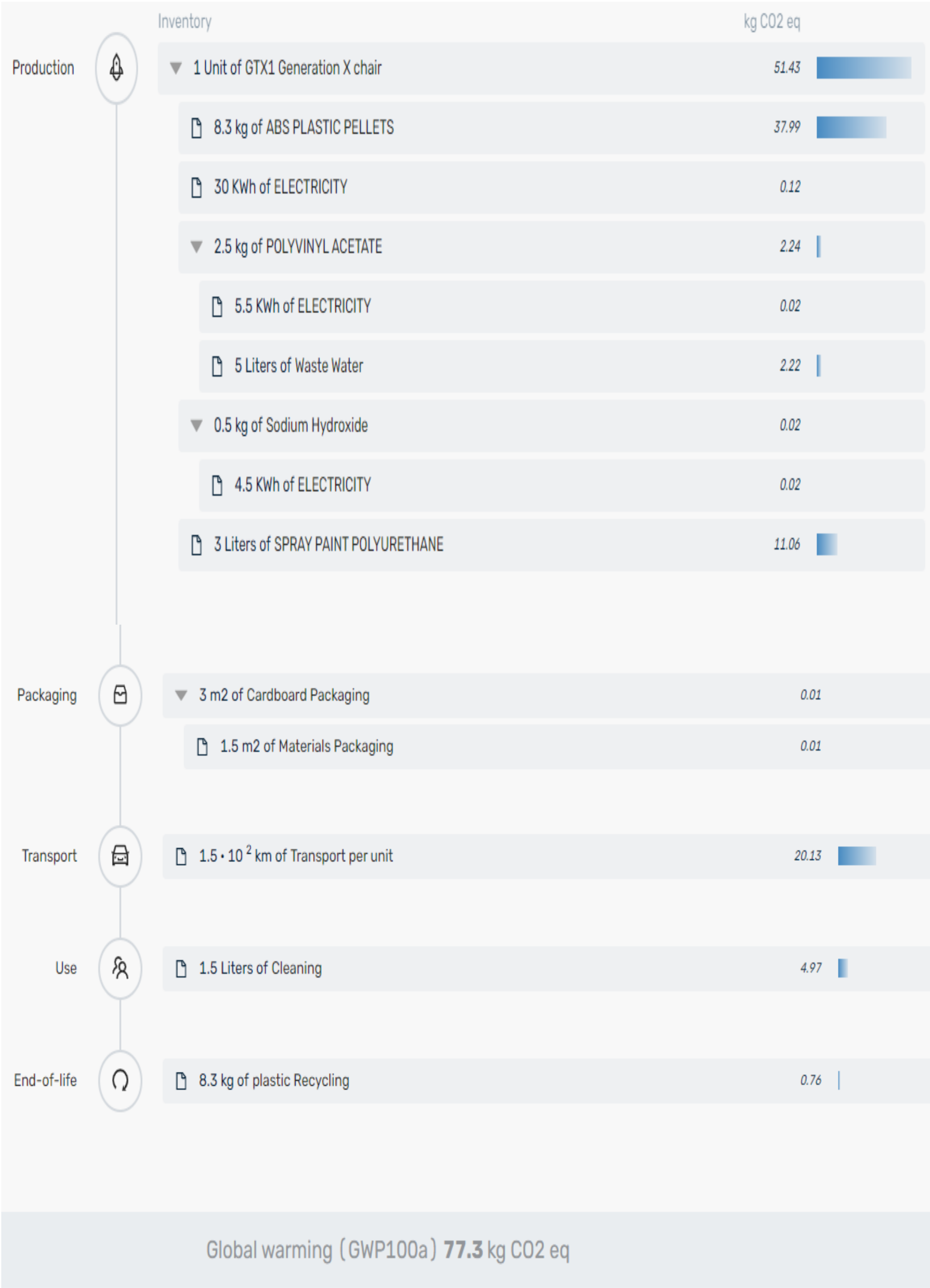


Fig. 142 Top Level summary of GTX1 Chair Product and Lifecycle Analysis (Fox.A,2022)

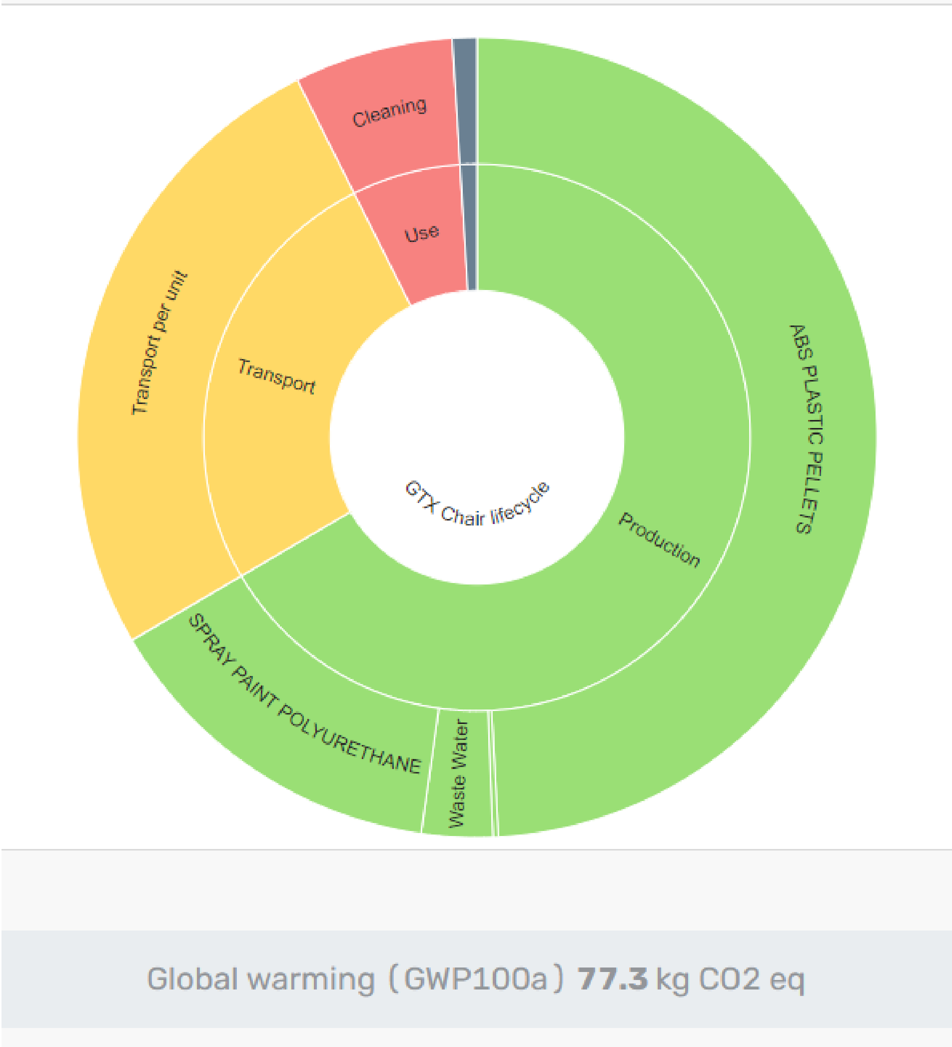


Fig. 143 Sunburst Diagram of relative elements in the GTX1 Chair Product and Life Cycle (Fox.A,2022)

Constraints and boundaries for this analysis are as follows:

The Environmental Review will only take account of primary and secondary processing together with estimated logistics. Primary extraction and material refining operations and subsequent processing of the raw materials will not be considered. This is an illustration of the impact of varying manufacturing methods only.

In a manufacturing organisation where the end results are critical for product environmental certification these additional elements should be added to the analysis to give a full Cradle to Grave Estimation of Product Environmental Impact.

7.5.1 Traditional Product Manufacturing

The traditional manufacturing model adopted here utilises elements of modern CNC manufacturing and other electronic technologies such as Radio Frequency for glue curing. It can be seen in the summary of machine centres required for the manufacture of the ST1 Chair that the range of machinery required is quite extensive and would require a sizeable floor area in which to operate. In addition due to the requirements of Health and Safety, (which would include PUWER and COSHH regulations etc.) the various processes must segregated and would also have the need for appropriate vapour and waste particulate extraction. This has an impact on the power needed and the potential environmental impact of the resultant products. The diverse range of materials used in the construction of the ST1 Chair also require additional transport to supply the manufacturing unit with raw materials and components for processing. This process would be very much static and based in an area with the products being shipped out from that site on completion.

7.6 Discussion and Conclusions

The Lifecycle Analysis of the products is by its very nature an estimate of the impact as the selection of references from the databases is to some degree a 'best fit' choice as one only knows so much about the way in which the element was constructed. However, by using similar references for both products the comparison has some validity and is a good guide to explore alternative solutions and providers of materials etc. For example, if we use Wind Power Generated in the UK as the electricity source for both scenarios then the comparison based on the usage is valid, this can then subsequently lead to the exploration of other sources and the impact of those changes can be compared to the original scenario. (Change Wind Generated UK power to French generated power through Nuclear Provisions for example)

The comparison of the Traditionally manufactured chair to the Additively Manufactured Generative Design returned an estimated result of:

Traditional Manufacture 117 Kg CO2 Eq. compared to the Generative Additive Manufacture of 77.3 Kg C02 Eq. Showing in global terms a reduction in Environmental impact for CO2 Eq. of 33.94 %. This is a significant reduction and although it is an estimate, it does show that there is very great deal of potential in adopting this approach in furniture manufacturing from the Environmental Impact standpoint.

In terms of the manufacturing methodologies employed to manufacture the two products. The scale and diversity of the manufacturing fixed capital resources required for the creation of the metal and wooden chair ST1 an estimated Standard Hourly cost of £20 is applied to determine the final unit cost. This is due to the higher floor area requirement, Health & Safety requirements, waste management and the higher skill levels required to achieve the output. The makeup is £11.00 per hour Labour and £9 per hour overhead contribution.

In comparison the GTX1 Additively Manufactured Chair achieves and estimated hourly Standard Cost of £18 per hour. As the skill levels required are lower being estimated at £10 per hour and the overhead contribution is slightly less at £8 per hour.

These combined with a material cost per unit (volume discounts are not applied to these as the volumes are unknown) are £30.50 for the ST1 Chair and £25.75 for the GTX chair respectively.

These elements equate to the following ex-factory price for the two comparative units:

<u>ST1 Chair</u>

8.85 Std Hrs x £20.00 Standard Hr. Cost = £177

£177 + £30.50 materials cost per unit = £207.50

£207.50 x 1.05 factory markup = £217.88 Estimated Ex- Factory Price

<u>GTX1 Chair</u>

10.01 Std Hrs x £18.00 Standard Hr. Cost = £180.18

£180.18 + £25.75 materials per unit = £205.93

£205.93 x 1.05 factory markup = £216.23 Estimated Ex-factory Price

The results of this high-level cost estimate indicates only a marginal direct cost variance from the conventionally manufactured chair to the Robot Based Additive Manufactured Chair. However, there are several issues which are not apparent just from looking at these isolated costs alone.

Although the manufacturing time for the GTX1 chair is longer when compared to the traditionally manufactured ST I Chair, what is not immediately apparent is that the Additive Manufacturing process results in a completely finished unit of production in one cycle and in the next cycle a new product design (or a customised variant) may be manufactured with virtually zero setup. Whereas the ST1 traditionally manufactured chair passes through a series of independent routing operations. Each requiring an element of setup time, hence the need to run multiple components in on operation. This batching extends the lead time from order to customer receipt and hence is a visible lead time to the client. This can only be overcome to some marginal extent by the use of Transfer Batches allowing components to move forward in the routing before the last operation is complete or by the employment of a One-Piece Flow Manufacturing or a Single Minute Exchange of Die (SMED) exercise to reduce setups as far as possible. (or a combination of all 3!) However, to achieve this practically this is very challenging and requires an extremely high level of skill and traditional process knowledge to achieve using trained Six Sigma Production Engineering teams.

Robot Based Additive Manufacturing with its flexible multi-product capability affords these benefits due to the very nature of its one cycle production process. Hence its ultimate lead time using Additive Manufacturing will be much shorter, more flexible and less visible to the customer.

This high-level comparison of Product Environmental Impact combined with the evidence of enhanced manufacturing flexibility the potential for ultimate 'Leagility' and customised manufacturing suggests that there is significant scope for further research and development in order to establish a full scale test cell for actual product manufacturing and the development of designs for the future of the Furniture Manufacturing Industry.

8 Chapter 8 Conclusions

8.1 Research Summary

Government initiatives to encourage the development of more flexible and agile sustainable manufacturing systems of the future has driven fast developments in Additive Manufacturing. The factors seen today affecting our climates and environments are key drivers towards further development of systems and procedures that will allow humanity to maintain and enhance the biosphere.

This research in its focused area of study lays out a conceptual platform and methods for the assessment and leverage of potential from disruptive technologies. TRIZ tools allow the cross-fertilization of ideas from one industry to another by thinking completely ‘out of the box’.

It has been demonstrated that Industrial Robot Based Additive Manufacturing has potential way beyond that of a prototyping process. It has the potential to be developed further into an alternative to Traditional Furniture Manufacturing. This transformation offers more sustainable products, manufactured through distributed manufacturing hubs, thus significantly reducing logistical requirements. Distributed Manufacturing also offers the potential for supply chain future proofing against more volatile situations such as those demonstrated during the recent Covid Pandemic and the Russian Invasion of Ukraine. These methods are transferable to other industries and supply chains to maximise the overall potential.

Each element of the integrated research platform has its strengths and weaknesses and these are assessed as being:

<u>Generative Design</u>

There are many strengths of this approach to Furniture Product Design since the rapid development and power of Cloud Processing capabilities. This has enhanced the commercial Generative Applications requiring much less programming capability to achieve outstanding results. Overall, the iterations produced are exceptional and very thought provoking especially when it is appreciated that there is the capability to produce them through the medium of Additive Manufacturing. This design technique leverages the strengths and advantages of Additive Manufacturing giving significant aggregated benefits. These creative aspects combined with the ability to assess and modify the designs pre-production enhance the ability to achieve ‘First Ideal Solutions’ and furthermore the ability to manufacture ‘Right First Time.’ These elements combined with the speed of development bring Mass Customisation and Prosumption a step closer to reality with far less resource exhaustive processes for Furniture Manufacturing.

As with most innovative technology approaches there are some weaknesses to be overcome. The re-education and the bringing of traditional Furniture Designers onboard could prove difficult initially. There are also quite a large number of redundant iterations created during a typical study which need a Human Designer to assess their potential or suitability to progress further. This combined with the (current) inability to force the symmetry of the iterations necessitates a requirement for the subsequent post-processing of geometries to achieve this if it is an important criterion in the final design.

Robot Based Additive Manufacturing

The key strength of this tool in manufacturing is its ability to produce an infinite variety of different products without the traditional burden of high changeover and setup times. The accuracy and repeatability are well within the parameters necessary for Furniture Manufacturing, and this coupled with the ability to process a wide variety of materials with the same equipment makes it a powerful methodology for the manufacturing of furniture in the future.

This flexibility combined with the ability to economically print elaborate structures, traditionally uneconomic using the established methods of manufacturing, makes this disruptive technology a strong contender to take over from these traditional practices in the medium term. Research into Voxel Printing and freeform printing have the potential to make this approach even stronger and accentuate its inherent strengths further.

Areas of weakness take the form of the need for support structures under certain criteria. This adds post processing cost and contributes to the Environmental Impact of the process outputs. This together with the restricted ability to change material density and color throughout the print volume hampers the ability to print variable product characteristics. This could be an incredibly significant area of further research where programmable volumetric characteristics can be altered and other methods of materials curing can be investigated e.g., UV Curing of polymers, Printing with 3D toolpaths and additional axes.

TRIZ

The key strengths of this technique for the application of Disruptive Technologies in Furniture Manufacturing are that it forces one to consider the overall aggregated system benefits as opposed to 'Islands of Automation.' The generic inventive principles encourage one to think 'out of the box' in applying them to the area being examined. Its aim to consider contradictions in the System has the potential to develop unique solutions which would otherwise be disregarded. This approach to inventive problem solving undoubtedly has its own strengths and is in my opinion a very necessary support and extension to enhance conventional process improvement methodologies. It takes the system analysis to a whole new level of 'Blue Sky Thinking.'

The main potential weakness is in the user, not the system, as it requires the innate ability of the user to think laterally and intuitively when looking at a potentially familiar problem. It reminds me of the adage 'Eyes are useless if the Mind is blind'!

There is a potential problem in getting traditional Industrial Engineers to engage in this type of analytical activity.

Aesthetics and Forms

The realisation of original & novel aesthetic forms is a key strength of Generative Design. These tend to be (but not always) of an organic nature which can be considered as both a strength and weakness depending on your viewpoint. The originality of these iterations, which exceed the capabilities of a human design team, is a significant strength of Generative Design for Furniture Manufacturing. The creation of new styles and forms in a short timescale can only be beneficial to the overall Furniture Design Community. This combined with the ability of clients to visualize the designs with photorealistic renderings pre-production can only enhance the level of customer service & satisfaction.

The creative element of generative design is one of its strengths, but it can also be a disadvantage in that it is challenging to control the forms produced. To this end a good working knowledge of loads and pressures relating to Furniture Structures is required to achieve meaningful iterations. The adage 'Rubbish in, Rubbish out' can be true in the case of generative design as it relies on these parameters alone to produce the iterations.

One further intangible weakness may be that the customer base does not like Generatively Designed forms and structures. This can only be gauged by market research and customer perception exercises.

Environmental Impact Analysis and LCA

Environmental Impact and Life Cycle Analysis have many strengths, among these are, the ability to create studies to undertake benchmark comparisons between products, organisational environmental performance and potentially Inter-organisational comparisons. These applications have the potential to highlight areas of significant impact allowing them to be addressed and return the maximum reduction in 'harms.' Even without a direct comparison to other products, the LCA platform can be used to undertake 'what-if' scenarios to assess alternative sources of materials, energy, process types etc.

Another strength is the ability to look completely upstream to primary materials extraction etc. which provides an insight into these impacts, which are often invisible to the secondary manufacturing operation. In the same vein, one can also look downstream to the end-of-life scenarios for the products or services. This gives and informed view of the best options at this stage of the product life, whether that be, designing for '2nd Life' or building in the potential for refurbishment or Restoration etc. and how these may then impact the overall Life Cycle Impacts of the products.

Life Cycle Analysis is at best an educated estimation of the impacts, therefore there is a potential weakness in the inconsistent use of databases and the very real need to understand what each element is made up of to produce a truly representative picture. Consistency of application can also be a problem when comparing different products etc. as one must compare like for like. Unless of course you are consciously changing an input to assess its affects. It is therefore a process of incremental improvement in terms of collecting historical data and information to better inform the process over time and gain more accurate illustrations of the Lifecycle.

8.2 Contributions of the Research

This research has made a positive contribution to the concept of future manufacturing opportunities in an otherwise very conservative furniture industry. The LCA although limited in scope has demonstrated a positive potential of the new methods to reduce environmental impacts by manufacturing generative additively manufactured products. Although unit prices in both approaches were similar the requirements for large diverse centralised manufacturing facilities is reduced significantly, thus reducing capital investment requirements. Additional benefits also include a flattened Bill of Materials (BOM), greater potential for recycling end-of- life products due to a reduction in mixed material usage.

The research demonstrated practically the physical configuration of a test robot cell, integrating all the necessary hardware and software to produce a functioning Industrial Robot Based Additive Manufacturing (IRBAM) unit for scaled Furniture Products. This cell configuration is easily adaptable to full scale production with larger plant availability. This cell also demonstrates the potential to manufacture larger furniture products and details how this may be further enhanced with the use of external axes.

Both Cloud based Generative Design and Shape Grammar creation & manipulation of Furniture Product forms have been demonstrated to hold enormous potential for disruption to traditional design practices & the development and exploitation of, previously unachievable, exceptional aesthetic Furniture Forms. With further refinement and additional software development these techniques have potential to revolutionise this traditional industry in line with current environmental and digital manufacturing goals of flexibility and agility. The platforms' ability to compare and contrast product characteristics and performance pre-manufacture further enhances the sustainability of the products through 'Right First Time' manufacturing.

The application and demonstration of the LCA methodologies to the Furniture Products not only allows traditional furniture manufacturing organisations to identify their 'environmental hotspots' but also demonstrates the potential for the development of marketing USPs for communication to far more environmentally educated customer groups.

In Summary the contributions to knowledge resulting from this research, in priority order, are as follows :

- Demonstrated the application of Generative Design and Shape Grammar to create sustainable, aesthetic, and easily mass customisable furniture products via Robot Based Additive Manufacturing (RBAM).
- Established the method to create previously uneconomic furniture structures in a sustainable manner using Robot Based Additive Manufacturing, creating thought-

provoking aesthetic qualities and unique functionalities with the potential to leverage the added functional benefits of emerging smart materials technologies.

- Development of an integrated problem-solving strategy for the analysis and application of disruptive technologies for the future development of Sustainable Furniture Manufacturing.
- Creation of a physical Robot Based Additive Manufacturing Cell integrating the generative designs and robot-based additive manufacture with potential extension to a full-scale manufacturing platform and demonstrating these integrated Design to Manufacturing technologies may also be instrumental in producing sustainable products which are far more appealing to an increasingly demanding and environmentally aware customer base.
- Demonstrated the potential of Environmental Product Impact Profiles of Generative Designs to inform and create Unique Selling Points (USP) to customers through assessment of the product Life Cycle Assessment (LCA).
- Reviewed and evaluated of these developments for extended and future research development.

8.3 Suggestions for Future Research

Although examined briefly in as context in this research, materials developments for Additive Manufacturing remains an area of great potential for future research. The development of materials for smart 4D functionality and a move away from petrochemical based materials offer significant potential for more significant ‘Mass Customized’ products but also a major potential to reduce or even eliminate product environmental impacts.

Currently many software options are still quite manually labour intensive to develop products, but with the emergence of Cloud based computing together with the advancement of AI and machine learning there is great potential for a step change. The convergence of Additive Manufacturing & AI based ‘Ontology’ approaches to smart manufacturing systems that are linked to the manufacturing execution software platforms would be a highly productive development. This would potentially allow for manufacturing process datasets to control the application and execution of manufacturing rules for different classes of product without onerous manual interventions. This sort of development would greatly enhance the overall intelligent digital connectivity to the automated production environment and shrink extensively the design to manufacturing lead time.

Further to this research into noncontact Quality Control & Assurance of the process through interactive technologies such as ‘fringe projection’ would further enhance the ability to produce right first-time products and reduce wastage.

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APPENDIX A – Materials Development and considerations

A 1 Movement from Petroleum Based to Bio Based Polymers

There is movement towards the development of Bio-based Polymers for use in conventional processes and the emerging technologies such as Additive and Hybrid Manufacturing.

A.1.1 Shift to Bio-based Polymers

The direction currently is from petrochemical based polymers such as:

- Polyvinyl Chloride (PVC)
- Polyethelene (PE)
- Polypropolene (PP)
- Polyurethane (PU)

To bio-based materials forming a number of natural and renewable base materials:

- Polylactic Acid (PLA)
- Polyhydroxy Fatty Acid (PHF)
- Polyethelene Terephthalate (PET)
- Bio Based Polyurethane (PUR)
- Polyamides (PA)
- Polyhydroxybutyrate (PHB)
- Polypropylene Carbonate (PPC)

These bio-plastic alternatives require far less or no fossil fuel resources in their manufacture, reducing CO2 emissions. They also degrade to basic components water, oxygen and compost. It is possible with future developments that these new bio-polymers can replace 70 % of conventional plastics.

A 1.2 Experimental polymer developments

- **Bacterial Cellulose**

Xylinum stool Janis Hulsen

Suzanne Lee, Central St Martins

Creating bacterial cellulose material, Suzann Lee, Central St Martins.

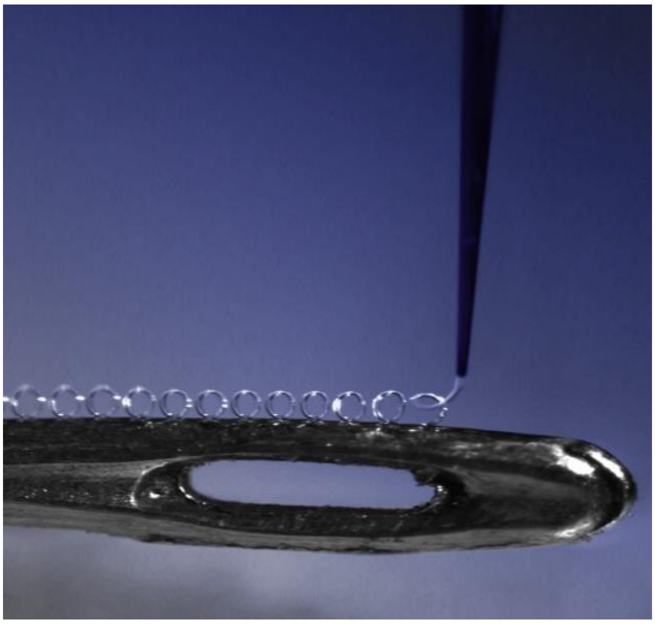
- **Milk Protein Fibers & Casein**

Protein Range, Tessa Silva-Dawson

- **Spider Silk Proteins**

“The silk protein coils upon itself like a spring. Each loop of the spring is attached to its neighbours with sacrificial bonds, chemical connections that break before the main molecular structural chain tears. To break the protein by stretching it, you need to uncoil the spring and break each of the sacrificial bonds one by one, which takes a lot of energy. This is the mechanism we're seeking to reproduce in laboratory,”

Gosselin F., Therriault D., Passieux R., Polythechnique Montreal



Bio-polymer derived from spider silk. Polytechnique Montreal

- **Soy Fiber and Polyols**

Soy polyols can be used to produce a variety of polyurethane products including moulded automotive foam, slab stock foams, viscoelastic foam, froth and rigid foams. Soy polyols can also enhance the sustainable profile of specialist polymers, coatings and adhesives.

- **Algae Based Polymers**

Scientific American suggests algae can take in three times the carbon dioxide emitted to produce a ton of ethylene therefore, acting as a carbon sink taking in more carbon dioxide than it gives out.

The process of getting ethylene from oil uses steam cracking, which requires a great deal of energy and emits a high volume of carbon dioxide in the process. Estimated to be around 3 tons per ton of ethylene.

Another hurdle for the researchers to clear is to ensure that algae production costs, estimated at around \$3,000 per ton, will at some point match current prices of ethylene which are approximately \$600 to \$1,000 per ton. (Scientific American)

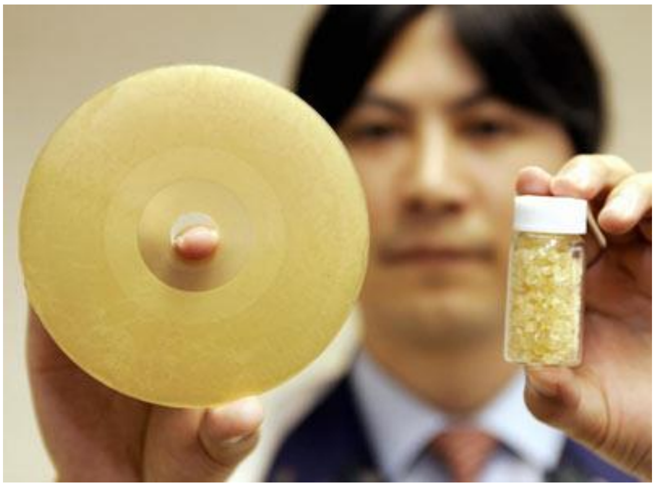
- **Carbon Dioxide Polymers**

Carbon dioxide polymer, Novomer.

In the region 60 % of the 'Greenhouse Effect' is estimated to originate from Co2 emissions. In response to this researchers are examining the production of Bio-Polymers that utilise CO2 in their creation.

Materials such as Polyhydroxy butyrate (PHB) made from palm oil has similar properties to ABS, and Polyurethane (PUR) is a suitable substitute a number of applications E.g. insulation, fridge production & mattress making in the bedding industry. The Polypropylene Carbonate plasticiser constituent is made up of as much as 40% carbon dioxide from waste gasses.

- **Starch, Collogen & Soya**



Starch polymer Blueray disk, Yoshikazu, Getty Images

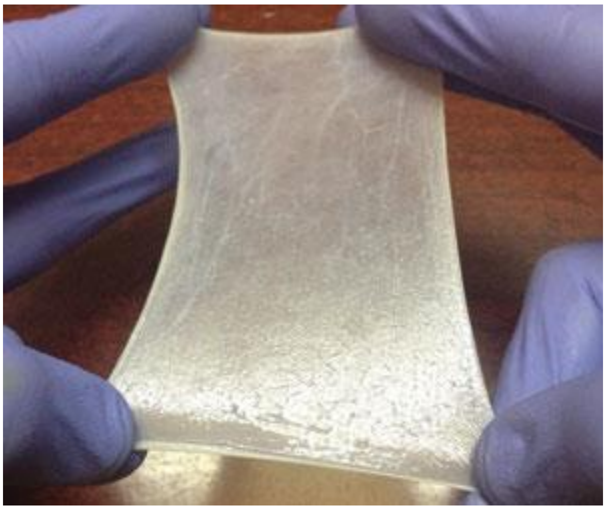
Starch is largely used for the production of bonding agents which are bio-degradable. Commonly manufactured from the following natural source materials:

Corn	71% starch	**Potato**	82% starch
Wheat	74% starch	**Rice**	89% starch

Collogen is an animal derivative again currently in wide use for the production of bonding materials such as:

Bone Glue	Furniture Restoration
Hide Glue	Bookbinding
Fish Glue	Fabric and inlay work

Biopolymers are now finding ‘high tech’ applications in medical applications such as the illustration below showing ‘Colloskin’



’Colloskin’, Polymer Medical Products, India

- **Lignin**

Lignin extracted from the cell walls of plant materials has thermoplastic properties, with good mechanical stability, and is insoluble in water. It is growing in significance in the production of wood based products as an alternative to petrochemical based polymer resins. Manufacturing of moulded ‘green’ products, such as the lamp/planter seen below are starting to emerge.

‘Liquid Wood’ Green Lantern, Planter Light, Romolo Stanco

- **Shellac**

An Animal based natural product as opposed to plant based. This materials is produced from the excretions of the Female Lac insect.

Lac Insect (Sternorrhyncha), Shutterstock

Hard and brittle at room temperature with a very shiny surface lustre and is insoluble in water this makes it ideal for use in surface coatings. It is also commonly encountered as a bonding agent in paints. Shellac does not have a very good resistance to heat. It was widely used as a traditional furniture and musical instrument finish. But it is also currently used as a coating in the food and pharmaceutical industries.

Shellac pharmaceutical casings, Shellac Industries, India

- **Natural Waxes**

Manufactured from both plant and animal sources they generally have very low melting points and are commonly used as surface finishing materials in bio-degradable designs and prototypes.

They do however hold fine detail and have extremely good surface qualities which make them very useful as master patterns in processes like lost wax casting etc.

3D Printed wax ring master & final cast product, Pixel Practice, NYC

- **Yeast Cultures**

There are a number of developments being investigated for the use of Yeast Cultures in the production of moulded and cast natural materials. One such example is that of ‘Grancium’ developed by DENK

This material is moulded under pressure allowed to dry and then fused at 1300 Deg. Celcius during which the Yeast Culture ‘Binder’ is burned away leaving the form which has similar properties to the natural stone.

Grancium 'Liquid Granite', outdoor wax burner, DENK Ceramics, Germany

A 1.3 Natural Composite Fibres

A 1.3.1 Fruit & Plant Fibres

- **Bamboo and biopolymer**

Bamboo and biopolymer extrusion, Materials Ambientes Ecologicos

Bamboo is a potential substitute material for solid timber The bamboo is crushed and usually pressed with phenolic resin to form the raw material.

- **Banana**

Banana Fibre 'bananaplac' vessels, Composites today

Materials such as 'Bananaplac' have been developed by the University of Rio de Janeiro. In this particular example the fibres are made into the compound material in conjunction with Bio-polyurethane (PUR)

- **Flax, Rye, Bulrush, Wheatstraw, Linen , Sisal, Hemp and Stinging Nettles**

Hemp Biopolymer glasses frames, Sam Whitten, Hemp Eyewear

In addition to the specific examples above there are a variety of other natural fruit and plant fibres which can be combined with Bio-Polymers to form natural bio-degradable composite materials with good mechanical strength properties. These include but are not limited to Flax, Rye & Wheat straw, Sorghum, Linen, sisal and even stinging nettles.

- **Seed & Nut Fibres; Poplar, Cotton & Kapok**



Poplar Fluff Fiber, Balconygarden.com   Cotton Seed Fluff Fiber, 4ever.eu   Kapok Fluff fiber, Google

- **Hazelnut, Macadamia nut, Peanut and Coconut fibres**

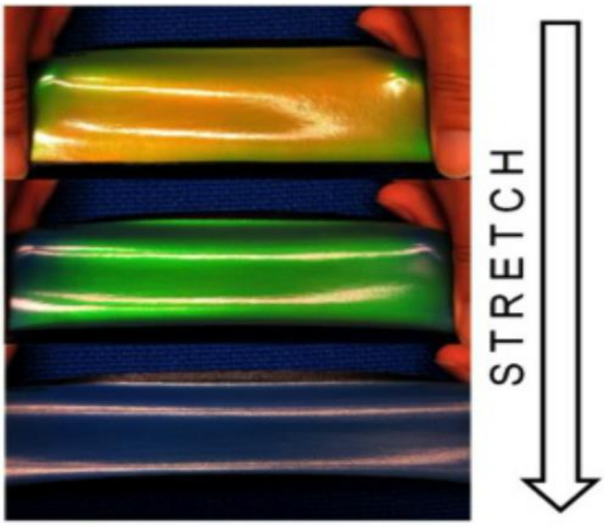
3D Printed Macadamia Nut Biopolymer, Sandra Loschke , Microtimber, University of Sydney

With the use of Composites and the development of 5D printing to orientate the fibres & to maximise strength there may be further benefits in reducing materials consumption through the minimalist design of the structures required.

A 1.4 Another Dimension:

When considering Additive Manufacturing as a process medium for the production of furniture it is important to not only consider the enhanced recycling potential of new materials but to also look at the potential for 4D printing ie. The further dimension being time where materials act in response to stimuli over a period of time to transform the products. This also has an impact on LCA as the products become adaptable and far greater utility for the Client. The development of interactive, reactive and smart materials have an immense scope for further research. These integrated with AI technologies would potentially create a Step Change in Furniture design functionality, satisfying the demands of an increasingly technologically aware end user.

- **Colour Changing**



Stretch colour change Opal Polymers, Cambridge University

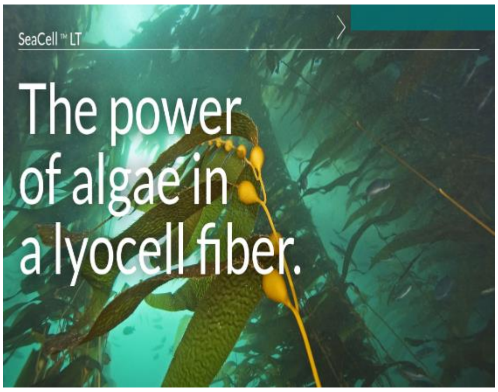
Temperature, Pressure, strain and fluid sensitive polymers are now being tested to signal through colour, changes to their immediate environment. Development of products in the clothing industry show the design potential. E.g. raincoats, umbrellas and shower accessories.

Water reactive color changing bath (Shutterstock)

- **Anti-bacterial**

For use in hospitals schools and other demanding environments where hygiene is critical the development of polymers with anti-bacterial properties could be very beneficial indeed.

For example algae skin protection using a modified 'Seacell' fibre



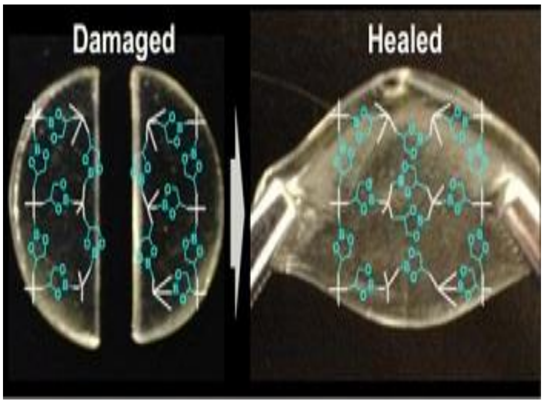
Seacell tm Smartfibre.ag

- **Heating & Cooling**

Solar heated patio chair, Sefar

An example of the fabrics and polymers being developed can be seen in this solar powered eco patio chair produced by Sefar smart fabrics as an alternative to the extensive use of patio heaters.

- **Self Healing**



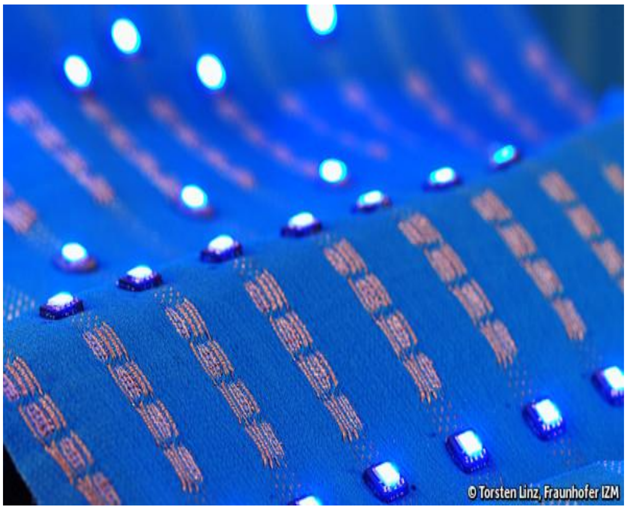
Damaged material 'healing' (Shutterstock)

The advantage of self-healing materials is self-evident. A great deal of development work has gone into this class of materials and they are now starting to become more readily available for everyday usage.

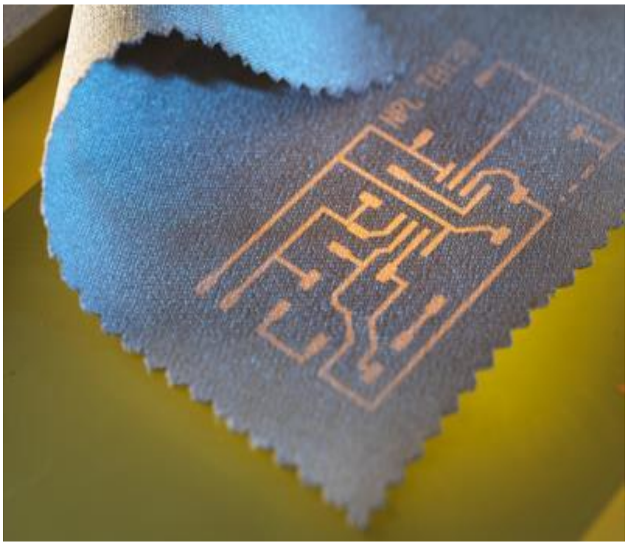
Scientists at the Frauenhofer UMSICHT and in other institutions have developed materials in the following categories which are classed as self-healing:

- Wear Protection coatings
- Hydrogels
- Polymers
- Elastomers
- Films
- Paint under UV light
- Polyurethane paints

- **Electro-active & integrated electronics**



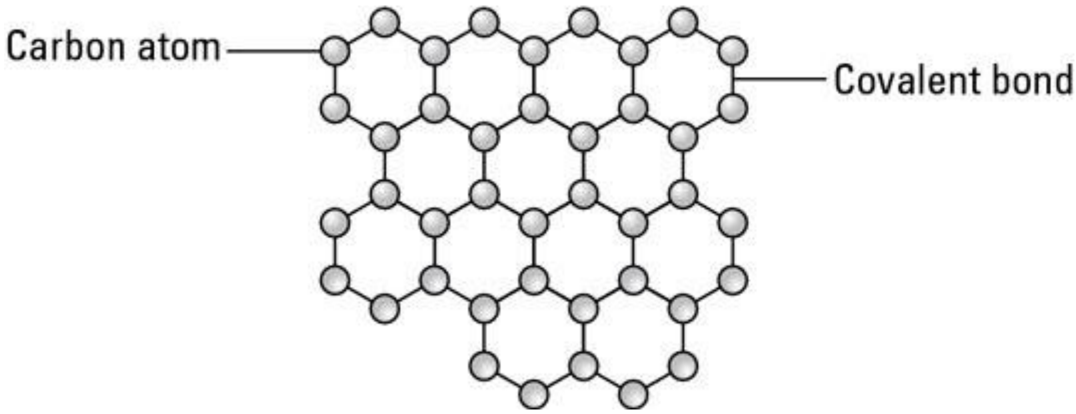
Embedded electronics in fabric, Frauenhaufer IZM



Printed Circuitry, Luxtura

The ability to print circuity, combine it with enhanced batteries, smart materials and the digital technology to quickly & sustainably produce the products will undoubtedly create so many new options for designers to provide Mass Customised products to a very demanding customer base who want quality, long life, upgradeability and also sustainable eco-friendly products.

- **Graphene**



Next generational materials such as graphene once developed and the manufacturing prices brought down to an acceptable level may provide a platform for a raft of further developments in both electronics and very high strength composites. At the present time difficulty and the inherent high cost of production is prohibitive for the use of this material in all but the very highest value added applications.

- **Expansive**
- **Expansive Microcells**

Materials that expand and contract when an external force is applied to them, the forces may vary in type from heat, load, moisture etc. These expansive microcells also have the possibility to develop a new dimension to aesthetic adaption in a product.

Expansive microcells in non-woven fabric, Composites Europe 2012

- **Thermoplastic Polyurethane Memory Foams**

  Already employed in some furniture applications, shape memory foam is used in the production of Upholstery and bedding products. This application can be further extended with the introduction of the ability to retain or reverse that shape memory when triggered to do so by an external stimuli.

Visco Elastic 'Memory Foam', Europa Foams

- **Gradient Materials**

This is an important step for 3, 4 & 5D printing to be able to achieve the accurate deposition of materials with graded properties in one single production cycle. The ability to be able to change the density and type of material deposited through the production cycle would enable the construction of complete products without the need for the manufacture of sub-assemblies containing these different material characteristics. This potential is becoming far more viable with the focus on programming through 3D Voxels rather than the traditional 2D Pixel. The ability to deposit materials via a true 3D toolpath and also alter the characteristics of that material will open up vast design possibilities for new product development.

- **Polymer Optical Fibres (POF)**

Light Conducting Fibres

GHOST CHAIR

Design by Ralph Nauta and Lonneke Gordijn for Drift

- **Flouride Poly Methyl Methacrylate (PMMA)**

'MIST BENCH'

Design by Gwenael Nicolas

APPENDIX B – Routings, Std Times for ST1 and GTX Chairs for Case study (Fox.A.,2022)

B .1 ST1 Arm Laminate routings and Standard Times

Component Routing

Handed Component : N Part Desc. : Beech Face Veneer Arm Rest

Model Name: Ripple Model No. : ST1 Part No. :ST1/004/001

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech face Veneer 300 x 80 x 0.5 Arm Rest	ST1/004/001	2	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.15	0.392
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.15	0.392
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.17	0.526
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.15	0.392
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.15	0.392
						Component Part Totals			2.094

Component Routing

Handed Component : N Part Desc. : Beech Core Veneer Arm Rest

Model Name: Ripple Model No. : ST1 Part No. :ST1/004/002

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Core Veneer 300 x 80 x 0.5 Arm Rest	ST1/004/002	11	1	001	Guillotin	Guillotine to rough cut length 310mm	0.2	0.15	0.392
			2	001	Guillotin	Guillotine to rough cut width 90mm	0.2	0.15	0.392
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.17	0.526
			4	001	Guillotin	Guillotine to finished Length 300mm	0.2	0.15	0.392
			5	001	Guillotin	Guillotine to finished width 80mm	0.2	0.15	0.392
						Component Part Totals			2.094

Component Routing

Handded Component : N Part Desc. : Beech Cross Laminate Veneer Arm Rest

Model Name: Ripple Model No. : ST1 Part No. :ST1/004/003

Part Name	Part No.	No.Off	eration sequen	Mc No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Euro Beech Cross Laminate Veneer 300 x 80 x 0.5 Arm Rest	ST1/004/003	2	1	001	Guillotin	Guillotine to rough cut length 310mm	0.2	0.15	0.392
			2	001	Guillotin	Guillotine to rough cut width 90mm	0.2	0.15	0.392
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.17	0.526
			4	001	Guillotin	Guillotine to finished Length 300mm	0.2	0.15	0.392
			5	001	Guillotin	Guillotine to finished width 80mm	0.2	0.15	0.392
						Component Part Totals			2.094

Component Routing

Handed Component : N Part Desc. : Adhesive Arm Rest

Model Name: Ripple Model No. : ST1 Part No. :ST1/004/004

Part Name	Part No.	No.Off	eration sequen	Mc No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Caesine Adhesive 500g Arm Rest	ST1/004/004	1	1	003	Mixer	Mix 500g grams Casein Adhesive	0.4	1.000	1.568
						Component Part Totals			1.568

Arm Rest Laminate Sub-assembly

Sub-assembly Routing

Handed : N Sub-assembly Desc. : Arm Rest

Model Name: Ripple Model No. : ST1 Sub-assembly No. : ST1/004

Part Name	Part No.	No. Off	eration sequen	MC No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Face Veneer	ST1/004/001	2	1	004	Roller	Adhesive to veneer faces with glue rolle	0.50	0.60	1.232
Core Veneer	ST1/004/002	11	2	005	RF Jig	Layup/ align face, core and cross lamina	0.50	0.75	1.400
Cross Laminates	ST1/004/003	2	3	006	RF Press	RF Cure adhesive	2.00	3.00	5.600
Casrine Adhesive	ST1/004/004	500g	4	007	5-Axis	Cut final dimension and edges	2.00	3.25	5.880
			5	017	M/BORE	Drill counterbore hole for Bolts	0.75	0.80	1.736
			6	008	Drum	Sand edges and faces	2.50	3.75	7.000
				018	S/KUKA	Load into jig and spray both sides of pane 2 Pack Polyurethane wet look glass	1.00	2.50	3.920
				019	DRYER	Panel through force drying tunnel	0.80	5.00	6.496
				020	DENIB		0.75	2.50	3.640
						Component Part Totals			36.904

B.2 ST1 Back Support Laminate Routings and Standards Times

Component Routing

Handed Component : N Part Desc. : Beech Face Veneer Back Support Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/002/001

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech face Veneer 650 x 550 x 0.5 Back Support Panel	ST1/002/001	2	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.975	1.316
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.975	1.316
			3	002	Stitcher	Stitch Leaves as necessary	0.3	1.105	1.574
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.975	1.316
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.975	1.316
						Component Part Totals			6.838

Component Routing

Handed Component : N Part Desc. : Beech Core Veneer Back Support Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/002/002

Part Name	Part No.	No.Off	Operation sequence	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Core Veneer 650 x 550 x 0.5 Back Support Panel	ST1/004/002	11	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.975	1.316
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.975	1.316
			3	002	Stitcher	Stitch Leaves as necessary	0.3	1.105	1.574
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.975	1.316
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.975	1.316
						Component Part Totals			6.838

Component Routing

Handed Component : N Part Desc. : Beech Cross Laminate Veneer Back Support Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/002/003

Part Name	Part No.	No.Off	Operation sequence	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Cross LaminateVeneer 650 x 550 x 0.5 Back Support Panel	ST1/002/003	2	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.975	1.316
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.975	1.316
			3	002	Stitcher	Stitch Leaves as necessary	0.3	1.105	1.574
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.975	1.316
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.975	1.316
						Component Part Totals			6.838

Component Routing

Handded Component : N Part Desc. : Beech Cross Laminate Veneer Back Support Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/002/003

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Cross Laminate Veneer 650 x 550 x 0.5 Back Support Panel	ST1/002/003	2	1	001	Guillotin	Guillotine to rough cut length 310m	0.2	0.975	1.316
			2	001	Guillotin	Guillotine to rough cut width 90mm	0.2	0.975	1.316
			3	002	Stitcher	Stitch Leaves as necessary	0.3	1.105	1.574
			4	001	Guillotin	Guillotine to finished Length 300mr	0.2	0.975	1.316
			5	001	Guillotin	Guillotine to finished width 80mm	0.2	0.975	1.316
						Component Part Totals			6.838

Component Routing

Handded Component : N Part Desc. : Adhesive Back Support Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/002/004

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Caesine Adhesive 500g Back Support Panel	ST1/002/004	1	1	003	Mixer	Mix 500g grams Casein Adhesive	0.4	6.500	7.728
						Component Part Totals			7.728

Back Support Laminate Sub Assembly Routings and Standard Times

Sub-assembly Routing

Handed : N Sub-assembly Desc. : Back Support Panel

Model Name: Ripple Model No. : ST1 Sub-assembly No. : ST1/002

Part Name	Part No.	No. Off	peration sequen	MC No	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Face Veneer	ST1/002/001	2	1	004	Roller	Adhesive to veneer faces with glue roll	0.50	3.90	4.928
Core Veneer	ST1/002/002	11	2	005	RF Jig	Layup/ align face, core and cross lamin	0.50	4.87	6.014
Cross Laminates	ST1/002/003	2	3	006	RF Press	RF Cure adhesive	2.00	3.00	5.600
Caesine Adhesive	ST1/002/004	500g	4	007	5-Axis	Cut final dimension and edges	2.00	5.00	7.840
			5	017	M/BORE	Drill 4 counterbore bolt holes	0.75	0.80	1.736
			6	008	Drum	Sand egdes and faces	2.50	6.00	9.520
				018	S/KUKA	Load into jig and spray both sides of pa 2 Pack Polyurethane wet look gloss	1.00	2.50	3.920
				019	DRYER	Panel through force drying tunnel	0.80	5.00	6.496
				020	DENIB		0.75	2.50	3.640
						Component Part Totals			49.694

B.3 ST1 Seat Panel Routings and Standard Times

Component Routing

Handed Component : N Part Desc. : Beech Face Veneer Seat Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/003/001

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech face Veneer 550 x 550 x 0.5 Seat Panel	ST1/003/001	2	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.825	1.148
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.825	1.148
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.935	1.383
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.825	1.148
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.825	1.148
						Component Part Totals			5.975

Component Routing

Handded Component : N   Part Desc. : Beech Core Veneer Seat Panel

Model Name: Ripple   Model No. : ST1   Part No. :ST1/003/002

Part Name	Part No.	No.Off	Operation sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Core Veneer 550 x 550 x 0.5 Seat Panel	ST1/003/002	11	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.825	1.148
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.825	1.148
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.935	1.383
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.825	1.148
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.825	1.148
						Component Part Totals			5.975

Component Routing

Handed Component : N   Part Desc. : Beech Cross Laminate Veneer Seat Panel

Model Name: Ripple   Model No. : ST1   Part No. :ST1/003/003

Part Name	Part No.	No.Off	Operation sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Euro Beech Cross LaminateVeneer 550 x 550 x 0.5 Seat Panel	ST1/003/003	2	1	001	Guillotine	Guillotine to rough cut length 310mm	0.2	0.825	1.148
			2	001	Guillotine	Guillotine to rough cut width 90mm	0.2	0.825	1.148
			3	002	Stitcher	Stitch Leaves as necessary	0.3	0.935	1.383
			4	001	Guillotine	Guillotine to finished Length 300mm	0.2	0.825	1.148
			5	001	Guillotine	Guillotine to finished width 80mm	0.2	0.825	1.148
						Component Part Totals			5.975

Component Routing

Handed Component : N Part Desc. : Adhesive Seat Panel

Model Name: Ripple Model No. : ST1 Part No. :ST1/003/004

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Caesine Adhesive 500g Seat Panel	ST1/003/004	500g	1	003	Mixer	Mix 500g grams Casein Adhesive	0.4	5.500	6.608
						Component Part Totals			6.608

Seat Panel Sub assembly routings and standard times

Sub-assembly Routing

Handed : N Sub-assembly Desc. : Seat Panel

Model Name: Ripple Model No. : ST1 Sub-assembly No. : ST1/003

Part Name	Part No.	No. Off	peration sequen	MC No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Face Veneer	ST1/003/001	2	1	004	Roller	Adhesive to veneer faces with glue roll	0.50	3.30	4.256
Core Veneer	ST1/003/002	11	2	005	RF Jig	Layup/ align face, core and cross lamin	0.50	4.13	5.180
Cross Laminates	ST1/003/003	2	3	006	RF Press	RF Cure adhesive	2.00	4.00	6.720
Caesine Adhesive	ST1/003/004	500g	4	007	5-Axis	Cut final dimension and edges	2.00	5.00	7.840
			5	017	M/BORE	Drill counterbore bolt holes	0.75	0.80	1.736
			6	008	Drum	Sand egdes and faces	2.50	6.00	9.520
				018	S/KUKA	Load into jig and spray both sides of pa 2 Pack Polyurethane wet look gloss	1.00	2.50	3.920
				019	DRYER	Panel through force drying tunnel	0.80	5.00	6.496
				020	DENIB		0.75	2.50	3.640
						Component Part Totals			49.308

B.4 ST1 Left Hand Facing Side Frame Routings and Standard Times

Component Routing

Handed Component : Y   Part Desc. : Back Rest and Arm Oval Steel Tube

Model Name: Ripple   Model No. : ST1   Part No. :ST1/001/01LH/001

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Backrest and Arm Tub LHF	ST1/001/01LH/001	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.75	1.064
			2	010	T/BEND	Bend to programmed profile	0.3	1.1	1.568
			3	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.8	1.344
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.25	1.624
						Component Part Totals			5.6

Component Routing

Handed Component : Y   Part Desc. : Lumber & Back Leg Oval Steel Tube

Model Name: Ripple   Model No. : ST1   Part No. :ST1/001/01LH/002

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Lumber and Back Leg Tube LHF	ST1/001/01LH/002	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.8	1.12
			2	010	T/BEND	Bend to programmed profile	0.3	1.12	1.5904
			3	011	M/TSAW	ut both ends to dimension and finished an	0.4	0.9	1.456
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.25	1.624
						Component Part Totals			5.7904

Component Routing

Handed Component : Y   Part Desc. : Front Leg & Seat Oval Steel Tube

Model Name: Ripple   Model No. : ST1   Part No. :ST1/001/01LH/003

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	etup Time	Basic Tim	Std. Time
Front Leg and Seat Tube LHF	ST1/001/01LH/003	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.85	1.176
			2	010	T/BEND	Bend to programmed profile	0.3	1.23	1.7136
			3	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			5.9584

Left Hand Facing side frame sub assembly routing and standard times

Sub-assembly Routing

Handed : Y   Sub-assembly Desc. : Side Assembly Oval Tubular steel LHF

Model Name: Ripple   Model No. : ST1   Sub-assembly No. : ST1/001LH

Part Name	Part No.	No. Off	peration sequen	MC No	Mc Desc	Operation Description	etup Time	Basic Tim	Std. Time
Backrest & Arm Tube	ST1/001/01LH/001	1	1	013	J/WELD	Load and locate to stops components Robot Welding Jig and cramp in position	0.75	1.25	2.240
Lumber & Back Leg Tube	ST1/001/01LH/002	1							
Front Leg & Seat Tube	ST1/001/01LH/003	1	2	014	W/KUKA	Start process to TIG weld all componen to form side sub-assembly	0.20	1.75	2.184
			3	012	LIN	Linish joints and surfaces as necessary suitable finish for powder coating	0.20	2.00	2.464
						Component Part Totals			6.888

B.5 ST1 Right Hand Facing Side Frame Routings and Standard Times

Component Routing

Handed Component : Y Part Desc. : Back Rest and Arm Oval Steel Tube

Model Name: Ripple Model No. : ST1 Part No. :ST1/001/01RH/001

Part Name	Part No.	No.Off	peration sequen	Mc No.	lc Desc	Operation Description	etup Time	Basic Tim	Std. Time
Backrest and Arm Tub RHF	ST1/001/01RH/001	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.75	1.064
			2	010	T/BEND	Bend to programmed profile	0.3	1.1	1.568
			3	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.8	1.344
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.25	1.624
						Component Part Totals	[redacted]		5.6

Component Routing

Handed Component : Y Part Desc. : Lumber & Back Leg Oval Steel Tube

Model Name: Ripple Model No. : ST1 Part No. :ST1/001/01RH/002

Part Name	Part No.	No.Off	peration sequen	Mc No.	lc Desc	Operation Description	etup Time	Basic Tim	Std. Time
Lumber and Back Leg Tube RHF	ST1/001/01RH/002	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.8	1.12
			2	010	T/BEND	Bend to programmed profile	0.3	1.12	1.5904
			3	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.9	1.456
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.25	1.624
						Component Part Totals			5.7904

Component Routing

Handded Component : Y   Part Desc. : Front Leg & Seat Oval Steel Tube
Model Name: Ripple   Model No. : ST1   Part No. :ST1/001/01RH/003

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Front Leg and Seat Tube RHF	ST1/001/01RH/003	1							
			1	009	M/CUT	Cut Oval Tubing to length	0.2	0.85	1.176
			2	010	T/BEND	Bend to programmed profile	0.3	1.23	1.7136
			3	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			5.9584

Right Hand Facing Side Frame Sub Assembly routings and Standard Times

Sub-assembly Routing

Handed : Y   Sub-assembly Desc. : Side Assembly Oval Tubular steel RHF
Model Name: Ripple   Model No. : ST1   Sub-assembly No. : ST1/001RH

Part Name	Part No.	No. Off	peration sequen	MC No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Backrest & Arm Tube	ST1/001/01RH/001	1	1	013	J/WELD	Load and locate to stops components Robot Welding Jig	0.75	1.25	2.240
Lumber & Back Leg Tube	ST1/001/01RH/002	1				and cramp in position			
Front Leg & Seat Tube	ST1/001/01RH/003	1	2	014	W/KUKA	Start process to TIG weld all componen to form side sub-assembly	0.20	1.75	2.184
			3	012	LIN	Linish joints and surfaces as necessary suitable finish for powder coating	0.20	2.00	2.464
						Component Part Totals			6.888

B.6 ST1 Metal Cross Framing Parts

Component Routing
Handed Component : N Part Desc. : Back Rail
Model Name: Ripple Model No. : ST1 Part No. :ST1/BR01

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Back Cross Rail	ST1/BR01	2							
			1	009	M/CUT	Cut Oval Tubing to roughcut length	0.2	0.85	1.176
			2	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			3	017	M/BORE	Drill 3 countersunk locating holes in one	0.6	0.75	1.512
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			4.1552

Component Routing
Handed Component : N Part Desc. : Seat Rails Oval Tube
Model Name: Ripple Model No. : ST1 Part No. :ST1/SR01

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Seat Cross Rail	ST1SR01	2							
			1	009	M/CUT	Cut Oval Tubing to roughcut length	0.2	0.85	1.176
			2	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			3	017	M/BORE	Drill 3 countersunk locating holes in one	0.6	0.75	1.512
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			4.1552

B.7 ST1 Third Party Hardware

Component Routing

Handed Component : N Part Desc. : Back Rail

Model Name: Ripple Model No. : ST1 Part No. :ST1/BR01

Part Name	Part No.	No.Off	Operation sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Back Cross Rail	ST1/BR01	2							
			1	009	M/CUT	Cut Oval Tubing to roughcut length	0.2	0.85	1.176
			2	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			3	017	M/BORE	Drill 3 countersunk locating holes in one	0.6	0.75	1.512
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			4.1552

Component Routing

Handed Component : N Part Desc. : Seat Rails Oval Tube

Model Name: Ripple Model No. : ST1 Part No. :ST1/SR01

Part Name	Part No.	No.Off	Operation sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Seat Cross Rail	ST1SR01	2							
			1	009	M/CUT	Cut Oval Tubing to roughcut length	0.2	0.85	1.176
			2	011	M/TSAW	Cut both ends to dimension and finished	0.4	0.91	1.4672
			3	017	M/BORE	Drill 3 countersunk locating holes in one	0.6	0.75	1.512
			4	012	LIN	Linish tube faces and bevel ends for weld	0.2	1.23	1.6016
						Component Part Totals			4.1552

B.8 ST1 Consumable materials associated with the Chair Production

Bought in Consumable Product Absorption

Handed Component : N Part Desc. : Third Party Consumables

Model Name: Ripple Model No. : ST1 Part No. :ST1/CONSUM/001;002;003;004;005;006;007

Part Name	Part No.	No.Off	peration sequen	Mc No.	Mc Desc	Operation Description	Setup Time	Basic Time	Std. Time
Linishng / brush Abrasives	ST1/CONSUM/001	1 m/unit				Bought in from SIA Abrasives			
Polyurethane Wetlook 2 pack spray lacquer	ST1/CONSUM/002	2 ltr				Bought in from Morrels Woodfinishes			
Coating Powder	ST1/CONSUM/003	500g per unit				Bought In from ISP Woodfinishes			
Degreaser	ST1/CONSUM/004	0.09 ltr/unit				bought in from ISP Woodfinishes			
Cardbaord packaging Recyclable	ST1/CONSUM/005	1.5m/unit				Bought in from Third Party			
Welding Gas (*Argon)*	ST1/CONSUM/006	1 ltr/unit				Bought in from Energas			
Tooling purchase and maintenanc	ST1/CONSUM/007	£0.70/unit				Bought in from/maintained CSM Tooling			
						Component Part Totals			0

B.9 Main Assembly

Main-assembly Routing

Handed: N Main Assembly description: Ripple Chair Frame

Model Name: Rippel Model No. : ST1 Assembly No. : ST1/MA001

Sub-Assembly/Part No	Part No.	No. off	eration sequen	MC No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Tubular Steel Side Frame LHF	ST1/001LH	1	1	R/JIG	013	Insert and locate 2 handed side assemblies plus 2 seat rails & 2 back rails into robot of axes welding Jig	1.1	1.25	2.632
Tubular Steel Side Frame RHF	ST1/001RH	1							
			2	W/KUKA	014	Start programmed cycle to TIG weld sub assemblies together	0.2	2	2.464
Seat Rails	ST1/SR01	2							
Back Rails	ST1/BR01	2	3	LIN	012	Linish joints and surfaces ready for powder coating	1.75	2.25	4.48
Laminated Back Panel	ST1/002	1							
			4	DEG		Degrease metal Frame in dip tank/Condo Line	0.75	2.27	3.3824
Laminated Seat Panel	ST1/003	1							
Laminated Arm Rest	ST1/004	2	5	P/COAT		Robot powder Coat frame and pass throu Heat Tunnel	1.6	6	8.512
Oval Tube End Caps	ST1/HRDWR/001	8							
			6	Assembly		Assemble Arm Laminates, Back Rest and to frame with threaded bolts. Insert Tube end caps to frame ends.	0.75	5.5	7
Threaded Insert & Bolt Se	ST1/HRDWR/002	12							
						Component Part Totals			28.4704

B.10 GTX Routing of the Flat Bill of Materials for the Generative TX chair frame Additive Manufacturing Process

Main-assembly Routing

Handed: N Main Assembly description: Generation X Printed Chair Frame

Model Name: Generation TX Model No. : GTX1 Assembly No. : GTX1/MA001

Sub-Assembly/Part Nar	Part No.	No. off	eration sequen	MC No.	Mc Desc	Operation Description	Setup Tim	Basic Tim	Std. Time
Chair Frame for Robot Base Additive Manufacturing	GTX/MA001	1	1	021	P/KUKA	Load Sliced Print design model to ROBOD workcell, heat print platten and commence Chair and support printing	7	601	608
			2	022	Dip Bath	Dissolve support structure in solvent bath	4	300	304
			3	023	Denib	Denib small blemishes and inclusions etc ready for spray painting	4	60	64
			4	014	S/KUKA	Apply polymer self levelling primer filler and warm air force dry	6	9	15
			5	014	S/KUKA	Apply polymer decorative surface finish t client specification and warm air force dry	6	12	18
						Component Part Totals			1009

APPENDIX C- Ecochain Mobius Comparative Chart Examples (Fox.A.,2022)

Volume

Von Mises Stress

<u>Materials Comparison: Min Factor of Safety Vs. Von Mises Stress</u>

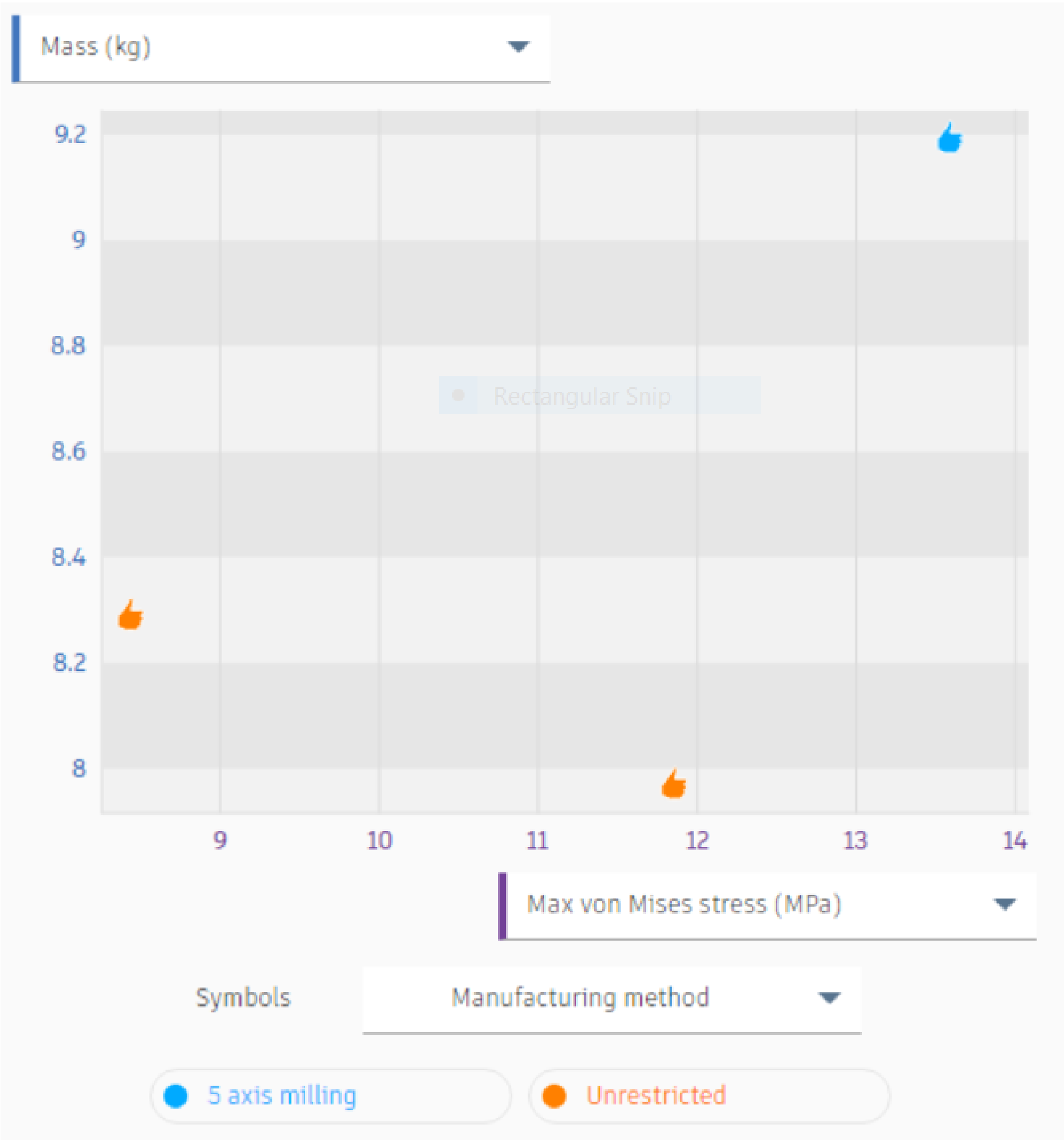
Minimum Factor of Safety

Von Mises Stress

Comparison by Manufacturing method: Mass Vs. Von Mises Stress

(This diagram is for illustration only as this generative study does not cover manufacturing methods in terms of design output comparison)

Mass



Von Mises Stress

APPENDIX D – Supporting Considerations & options when setting up an LCA Study

D.1 Product Category Rules (PCR) & Environmental Product Declarations (EPD)

Based on ISO 14040/44 is the standard ISO 14025 which outlines two concepts:

- **Product Category Rules (PCR)**
    - Guidelines for the calculation of the environmental impact of products within the same product grouping. These guidelines give strict requirements that give less room for interpretation than in a general LCA. Once these have been established a company can develop an Environmental Product Declaration (EPD) which contains concise relevant environmental information about a product.
- **Environmental Product Declarations (EPD)**

  These declarations consist of a number of environmental impact category indicator results. These impact factors are usually but not always limited to :

    - **Non-Renewable Resources** (with and without energy content
    - **Renewable Resources** (with and without energy content)
    - **Global Warming** ($Co2$ Equivalents)
    - **Acidification** (kmol H+)
    - **Ozone layer depletion** (kg CFC11 equivalents)
    - **Photochemical oxidant formation** (kg-ethane – equivalents)
    - **Eutrophication** (kg $O2$)

D.2 Approach to Goal and Scope Definition

The LCA illustrates a product, process or system lifecycle. The very nature of an LCA dictates that it is a simplification of a very complex system and as such this necessitates that the true picture will be distorted in some way. The key skill is to create a model in which this distortion does not affect the results significantly.

This requires careful planning and definition of the goals and limitations of the Study. The choices may include:

- The reason for conducting the LCA.
- Accurate definition of the product, its usage and its lifecycle.
- A definition of the unit for comparison.
- Description of System Boundaries and how co-production will be treated.
- Data quality, assumptions and limitations
- Intended audiences and method of communication
- The format of the study report.

Defining the Goal may vary considerably dependent upon the end use of the study being internal or for external comparison. Indeed, it could be that the study will be used both internally and externally, therefore the structure and data formats should reflect this end use.

Defining the scope in LCA studies is very much an iterative approach so these guidelines can generally be regarded as initial and can be modified as the study progresses.

In order to compare products, it is essential to establish a functional unit to allow comparison of products with different performance characteristics. This can sometimes be quite difficult as it is not always clear what function the product serves.

Defining system boundaries is also potentially challenging as any systems are interrelated in quite a complex way. The interrelationship of materials and products can carry on indefinitely. It is therefore essential to set a boundary around your subject in order to limit the extent to which you will analyses these inputs and outputs.

This may be determined as follows, for example:

1st Order : Only the production materials and transport are included

2nd Order : All processes during the life cycle are included , but capital goods are left out

3rd Order : All processes including capital goods are included (usually only the materials needed to produce the capital goods are included)

There are many fundamental questions to be resoved when setting these system boundaries, for example : What is the boundary with nature? Does the study include the growing trees that are harvested to produce furniture?

Many processes produce more than one product output. When the output of one product is dependent on the output of another.

System Expansion also known as **'consequential modelling'** can be applied when you want to know the consequence in a base line system of substituting one product for another. Multi-output processes can make this method of modelling very complex.

'Attribution Modelling' is employed when you want to know the environmental impact of products or processes and their lifecycle impact characteristics. Also for the comparison of two products with the same functional units. All environmental inputs and outputs are summed up from raw material extraction (Cradle) to waste treatment at the end of life (Grave), giving one an environmental footprint.

In the case of multi-output processes the environmental impact is divided between the co-product outputs. This can be done in one of three ways:

- **Sub-divide the multi-output process**
    - Identifying the inputs and outputs from each individual sub-process.
- **Determine a physical method for absorption**
    - This may be mass, volume, energy units etc.
- **Revenue as the basis for allocation**
    - This is used when physical attributes cannot be identified. Or Multi-output processes cannot be conveniently split.
        - E.g. If a Sawmill that produces planks also produces sawdust. The sawdust generates 15% of the revenue for the mill then 15% of the environmental load is absorped by the sawdust.
        - This one of the most commonly used methods of absorption used in LCA modelling. It is a good way of identifying waste and the relative importance of the output to the business.

D.3 Methodology for the use of foreground and background data

The collection of appropriate data is one of the hardest parts of the LCA process. A considerable amount of secondary data does exist but as with most scenarios some will not be available for specific processes or materials being utilised. In order to bridge this gap there are a couple of approaches that can be used. There are two distinct categories of data that should be considered.

- **Foreground Data**
    - Data specific to modelling the study and is specific to a particular product or specialist process
- **Background Data**
    - Generic data for the production of materials, transport, waste management etc.

In many cases this data will have to be collected from specific organisations. This can be done via questionnaire although this can prove difficult in practice. It is often necessary to foster a close relationship and trust with the suppliers of data, as they may see the LCA activities as a threat. It is essential to be able to reassure the providers of the aims, end use and how your outputs will be presented.

It should be remembered that some of the input and output information from commercial organisations can expose organisational technical and commercial confidentialities. Sometimes this issue can be resolved with the use of an impartial individual or body to facilitate the collection and supply summative information for the LCA study.

Depending on the goals and scope of the exercise a large part of this category of data should be available through databases or publications. One does have to exercise a high level of care when employing this data from databases to ascertain how the data was compiled and how well that fits to your end use in the study.

The **'Ecoinvent Database'** covers over 10,000 processes and is the integration of a number of Swiss lifecycle databases. A group of LVI experts from this group are responsible quality assurance, updating and adding to the Database.

There are a number of database variants available through Ecoinvent, which should cater for most background data requirements:

- Allocation Default, product and system processes
- Allocation Recycled Content , product and system processes
- Consequential , product and system processes

As the name suggests the Allocation data has the principals of Attribution Modelling applied whereas the Consequential data has had the principals of Consequential Modelling applied. Default signifies the absorption principal has been applied ie. Usually based on mass or revenue etc. The recycled reference means that it does not take into account any benefits derived from the recycling of any materials.

The **'unit and systems process'** option will provide data exclusively for that specific process and will provide references to other linked processes. E.g. 'creation a wooden chair' will start at the point where the raw materials are introduced to the processing steps.

The system process option would include all the upstream processes as the result of a complete LCA study and there will be no separate reference to the inputs and outputs of each separate processing stage. E.g. 'Creation of a wooden chair' would include all emissions from raw materials extraction through to the processing and assembly of the product.

The characteristics of the two approaches are as follows:

Unit Process	**System Process**
Transparent large process tree, that allows you to see the contribution of each element	Simple Process tree
Contains uncertainty information, which allows for statistical analysis	No Uncertainty Information
Slow calculations due to volume	Fast calculations

In essence one would normally use system process in the LCA Screenings and the unit process data when conducting a full LCA study.

D.4 Framework for widening the scope of Sustainability

There is a wider scope to sustainability, environmental impact is just one of many issues that companies want to address with the implementation of a sustainability review.

- **'Social Implications'** may affect employees, consumers and local communities etc. Th social aspects may include issues such as payment rates, health and safety concerns and training & development. The problem with these aspects is that they can be very far ranging and are also notoriously difficult to quantify.

It is essential to set boundaries around what is considered to be the most impactful for those stakeholders involved in the study.

This can be achieved using some a number of frameworks:

- **UNEP SETAC**
  - Guidelines for the social lifecycle of products highlight a number of social impacts which are linked to 5 groups of potential stakeholders. The procedural sheets advocate the use of performance indicators to that can be used to gauge the impacts.
- **The Global Reporting Initiative (GRI)**
  - Once again this method uses performance indicators and affords a certain level of standardisation to the reporting of social, environmental and economic impacts.
- **The United Nations Global Compact (UNGC)**
  - Addresses 10 principles covering 4 categories of Social and Environmental Impact. The impacts are global and not sector specific.
- **ISO 26000**
  - This is the ISO standard for social responsibility and is based around 7 core subjects covering aspects of social, environmental and organisational impacts.

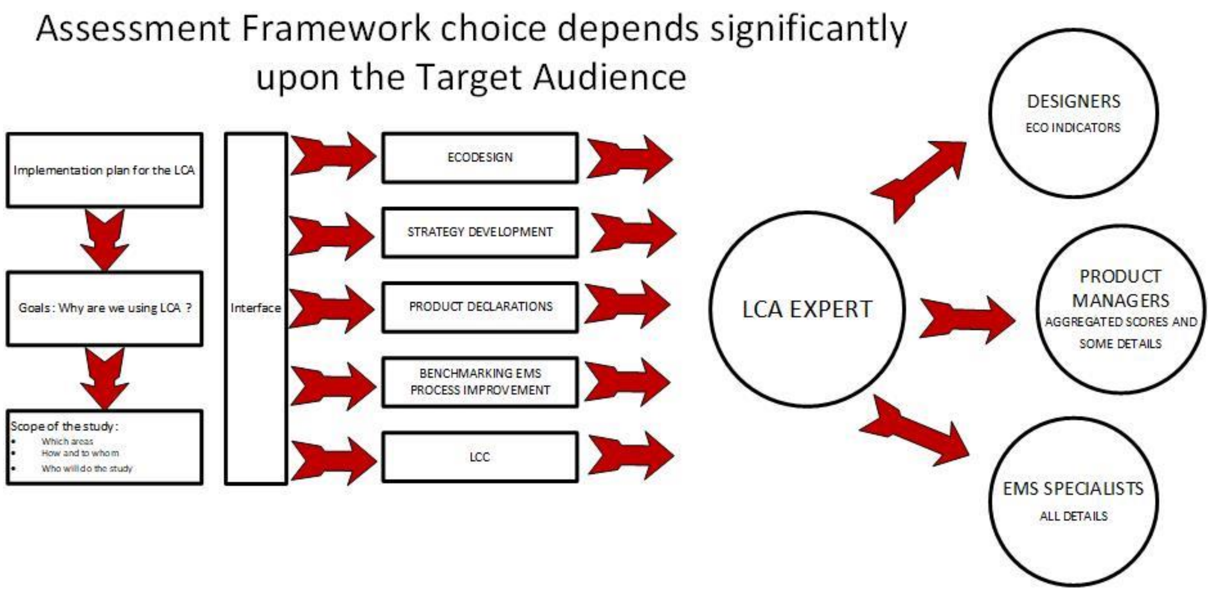
- **'Economic considerations'** are extremely difficult to add to an LCA and have been the subject of much discussion.

Important cost factors are not normally modelled, these could include factors such as:

- Investment
- Research
- Overheads
- Marketing

As LCA do not generally include a time factor these accurate economic elements are hard to model. This element is a high precision and crucial activity for most companies and is generally monitored closely by financial specialists. It is not an element for improvement through LCA Studies.

- **'Total Cost Assessment' (TCA)** is probably the best approach to highlight social and environmental issues. A systematic methodology is used to estimate these costs and the probability that they will transpire. From this a total average cost associated with sustainability can be established.
- **'Assessment of Impacts'** in most LCA studies do not develop their own methodologies for assessment but use an already established framework for their assessments of impact. The choice of this framework largely depends on the goals of the study and who it is to be communicated to.



D.5 Impact of ISO on assessment methods

The ISO 14040/44 standard defines a life Cycle Analysis as a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system through its lifecycle.

While the Impact Assessment is defined as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. The study should include classification and characterisation otherwise it can only be referred to as a Life Cycle Inventory (LCA)

Elementary flow	**Climate change**	**Ozone layer depletion**	**Eutrophication**
1.5 Kg of CO_2			
200-gram CH_4			
2 grams CFC 142b			
4 grams NO_2			

Now that the elementary flows are attributed to impact categories one cannot just say in the case of climate change that we have a total of 1702 grams of climate changing substances as they will all have their own individual level of impact. It is therefore necessary to apply the appropriate IPCC equivalency factor to determine the true level of environmental impact.

Elementary flow	Climate Change		Ozone Layer Depletion		Eutrophication	
	CF	RESULT	CF	RESULT	CF	RESULT
1 Kg of CO2	1	1				
10-gram CH4	25	0.25				
1 gram CFC 142b	2310	2.31	0.07	0.00007		
5 grams NO2					0.56	0.0028
Impact Category Indicator result		**3.56**		**0.00007**		**0.0028**
Unit of the Result	Kg CO2 Equivalent		Kg CFC11 Equivalent		Kg P Equivalent	

Example above shows the resultant impacts after the application of the Characterisation Factor (CF) The CF value is determined by the Impact assessment method chosen. There are cases where the elementary flow may cause impacts in a multiple of impact categories, the standard does mention splitting these between categories but in practice is rarely done allowing simultaneous impacts in different impact categories.

D.6 Selecting the method

The first question is regarding scope of the method. ISO 14044 requires that the study must address all relevant impact categories. No impact factors with a significant contribution should be omitted from the study. For this reason ISO have started to develop single issue standards such as Carbon Footprint and Water Footprint.

Once it is clear what the relevant issues of concern are, it is not always easy to find a method that sufficiently covers all these concerns. This is either because they do not currently exist in the LCA literature or software. It may also be, for example, that existing methods are developed for use in particular geographical regions which do not match the requirements or conditions of the study being undertaken etc.

As a newcomer to LCA studies it is ok initially to learn the process using default methods abut in the longer term it is essential to research these methods more fully and have a critical view on their selection.

D.7 Normalisation

Normalisation and weighting are used to simply the interpretation of the results. They are however regarded as optional by the ISO 14040/44 standards.

The benefit of normalisation are:

- Illustrates if an impact category indicator result is relatively high or low relative to a reference value.
- It also addresses the problem of impact category results being in incompatible units.

Elementary flow	Climate Change		Ozone Layer Depletion		Eutrophication	
	CF	RESULT	CF	RESULT	CF	RESULT
1 Kg of CO2	1	1				
10 gram CH4	25	0.25				
1 grams CFC 142b	2310	2.31	0.07	0.00007		
5 grams NO2					0.56	0.0028
Impact Category Indicator result		**3.56**		**0.00007**		**0.0028**
Unit of the Result	Kg CO2 Equivalent		Kg CFC11 Equivalent		Kg P Equivalent	
Normalisation Value	1.22E+4Kg CO2/yr		2.20E-2Kg CFC11/yr		4.15E-1Kg P/yr	
Normalised Result (yr)	**3.17E-4**		**3.18E-3**		**6.75E-3**	

The normalisation figure represents the annual person emission of that element.

- 11 tonnes of CO2
- 22 grams of CFC11
- 0.415 kg of Phosphate

These standard form values are entered as control values and the way the normalised result is produced is by dividing the Study Elementary flow value by the estimated annual emission value (Normalisation value) giving a relative to the annual emission level of that element. With this comparison the data can be put into perspective showing its relative contribution significance.

D.8 Weighting

Weighting is the most controversial and difficult method in Life Cycle Analysis. ISO does not allow the use of weighting in publicly disseminated comparative analyses. However weighting is used quite considerably for internal decision making.

Some choices for weighting are :

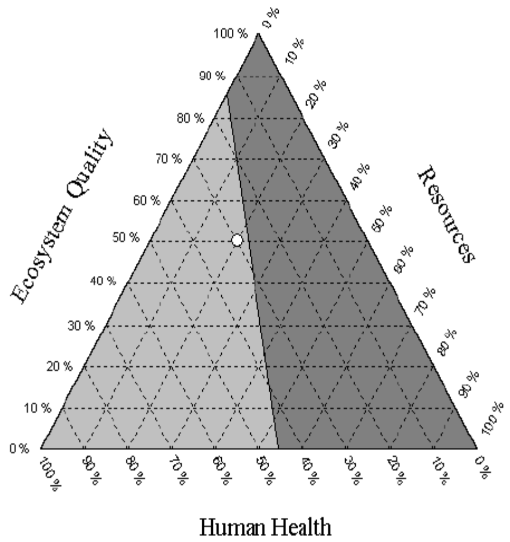
- **'Panel Weighting'** - a panel assesses the relative importance of each impact category and determines the default weightings. It is difficult to explain the exact nature of the impact factors and the panel can easily be influenced. So it is quite a subjective method.

- **'Distance to Target'** - this method a reduction target is set for each impact category and the further away the value is from the reduction target the higher the weighting. There are still some difficulties with this method as one does not know how important the targets are relative to one another. Reduction targets are also usually compromises and do not necessarily show the real need to reduce the particular impact category.

- **'Monetarisation'** - In EPS2000 all environmental damages are expressed in the same monetary unit**.** For example:
    - Environmental Load Units (Equivalent to the Euro)
      In the methodology the assumption is made that these different types of cost can be added.
    - Present Cost
    - Willingness to pay
    - Future extracting cost

This can be viewed as a weighting step in which all the various cost weight factors add up to one.

- The **'Triangular Weighting Concept'** has been developed by Hofstetter et al. 1999. It utilises a weighting triangle



Hostetter et al. 1999

In this method the triangle facilitates and open discussion of the factors affecting the product and under what weighting the products are more or less successful. It is a graphical method of displaying product comparisons for all possible weighting sets. This allows for a line of indifference to be established illustrating where weighting factors for two products have the same environmental load. It also identifies the weighting sets for which product A if favourable to product B and Visa Versa.

D.9 Interpretation

This is the final step of the LCA process and should, as the ISO 14044 standard states include checks to ensure that the conclusions are robustly supported by the data and that the procedures used were appropriate.

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