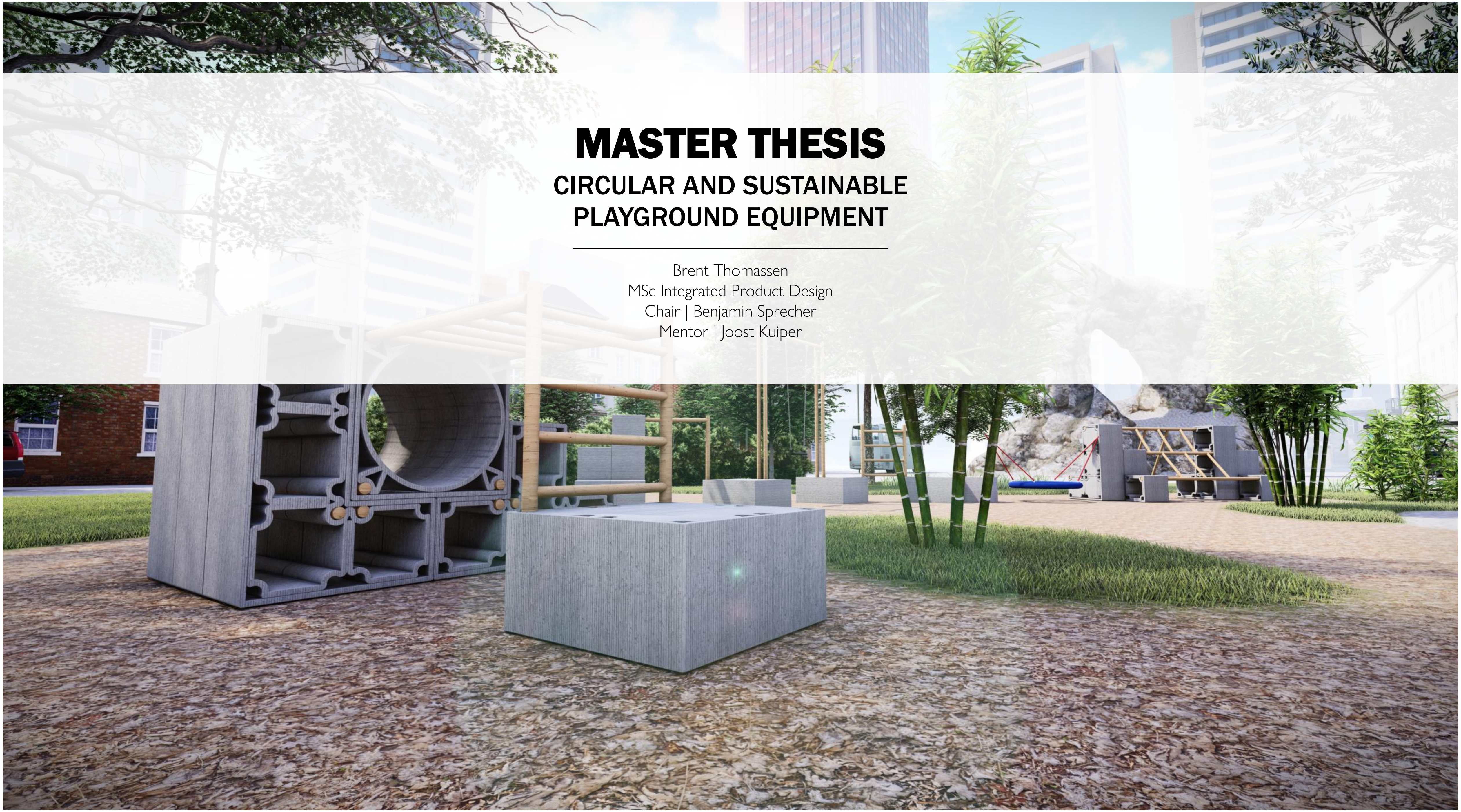

MASTER THESIS

CIRCULAR AND SUSTAINABLE PLAYGROUND EQUIPMENT

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Summary

The process of designing playground equipment

This project is focused on the development of circular and sustainable playground equipment (PE), as the Netherlands and its municipalities have set targets to become a Circular Economy in 2050. Furthermore, the PE should also encourage children to play outside more and engage in physical exercise. The reason for this being that children in the Netherlands do not play outside enough, which is often due to uninteresting playground designs.

The project started off with a theoretical framework, in which the 10R design strategies, such as reuse, repair and recycling, for the CE were examined on their effectiveness in playground design. Both academic literature and stakeholder & expert interviews enriched the knowledge needed to answer the research question. This resulted in the following design considerations which were the basis for developing the PE as described in this thesis:

- Create an interchangeable and customizable system with components that are easy to (dis-)assemble (product-service system with modular play modules)
- Design with a mono-material
- Design with a material which comes from a waste stream
- Design with a material which allows for form freedom
- Design with a material which is resistant to wear and tear and external conditions (cold, heat, moist, UV radiation, etc.)
- Eliminate redundant elements
- Design PE modules which can fulfil multiple play functions
- Design a connection system which allows for easy (dis-)assembly and consists of a minimal number of parts and different materials
- Design for effective and minimal repairs and maintenance
- Design with materials which can efficiently be recycled

I performed a study on an appropriate material and production method for the PE and from this I concluded on the use of 3D-printed Geopolymer with recycled aggregates, as it comes from a large Dutch waste stream, can be produced and efficiently recycled in the Netherlands, has a lifespan of several decades, allows for form freedom and colouring, and facilitates straightforward repairs and maintenance, making it an appropriate material for the Dutch CE. I was able to visit a 3D printing facility to get in contact with the material and production process, and even prototype my product here with 3D printing (Figure 1).

Based on conclusions derived from academic literature and a design session with 131 children aged 6-11 (Figure 2), I concluded that the play functions climbing and swinging & swaying, among several others, could encourage children the most to play outside more and engage in more physical activity. These functions are translated into the following themes: Treetop Retreat, Rapid Rush, Acrobatic Adventure and Hideaway Hunt, which are the focus of the designed PE (Figure 3).

Although the project lays out an interesting foundation for the development of circular and sustainable PE, more research and tests, for example on the appropriateness of the material and the connection system should be performed to conclude on its effectiveness within the CE.

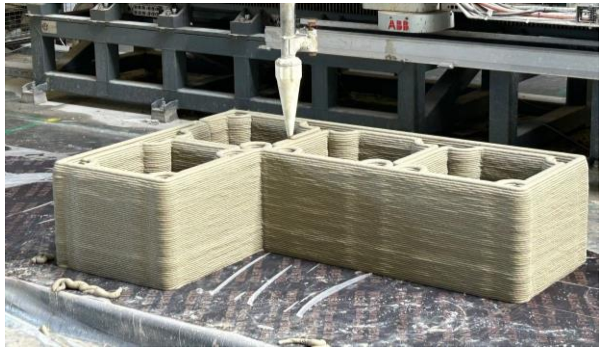

Figure 1: 3D-printing of product prototype

Figure 2: Design session with children

Figure 3: Final design proposal of the playground equipment

Acknowledgement

Appreciation for the people who contributed to my project

First, I want to thank Albert van Ee for providing me with the opportunity to work on this project and his continuing trust, help and enthusiasm throughout the process.

I also want to thank Benjamin Sprecher (chair) and Joost Kuiper (coach) for their coaching throughout the project. They helped me to make the most out of this thesis and project by providing relevant feedback, knowledge and new insights. I also want to thank them for their time, trust and flexibility.

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Furthermore, I want to thank Peter Paul Cornelissen for giving me a tour around the 3D-printing facility and providing me with knowledge and insights, and Pieter Bakker for consulting me on 3D-printing the prototype.

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Drawing by one of the students when asked: 'What is your experience with outside play?'

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1. Introduction

Context, assignment & research objective

1.1 Context | Decreased outdoor play due to 'boring' playgrounds

Outdoor play is crucial for children's mental and physical well-being [1], where well-designed play areas offer opportunities to increase physical, intellectual, social, and emotional development [2].

However, according to a study performed by Jantje Beton [3], at least 300.000 children in the Netherlands, aged 6-12, do not play outside, which is a concerning issue. This occurrence can partly be blamed on uninteresting playground designs as Oost-Mulder & Van Weert found that a substantial proportion (20-30%) of playgrounds are not used because of this [4].

Both Post et al. [5] (municipality of Almere) and Oost-Mulder & Van Weert [4] (municipality of Amsterdam) highlight the importance of providing playgrounds that are less focused on safety and more on adventure and variety. Ordinary play equipment is considered too static, and there is a demand for more imaginative and challenging playgrounds to stimulate children to play outside.

1.2 Context | Circularity and sustainability in playgrounds

The Netherlands aims to become a Circular Economy (CE) by 2050 [6], Where CE can be described as a system which focusses on increasing the circularity of both resources and energy within production systems by stressing a zero-waste vision. This is achieved by designing for the 10R design strategies, such as reuse, repair, remanufacturing or refurbishing, which provide innovative possibilities to deal with sustainability issues [7]. Because of this, Dutch municipalities are developing policies to align with the CE goals, like the Leidse ladder (LL) [8,9] (Figure 4) and the '5 strategies for circular playground design' by Metropool Regio Amsterdam [4] (Figure 5). These policies include the requirement for circularity in municipal construction projects, which playgrounds are a part of [8].

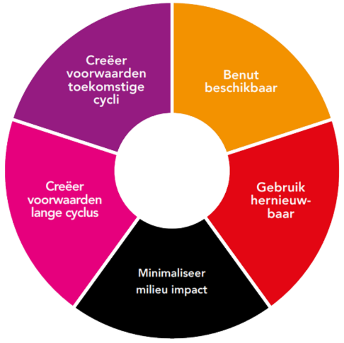


Figure 5: 5 strategies for circular playground design [11]

The LL is a tool developed by the municipality of Leiden to measure the degree of circularity in public spaces and consists of 8 circular design principles. Leiden will ask for 2 out of 8 of these starting from 2023, looking to expand this number in the near future. A higher score on the LL means less released CO2 equivalent and a lower MKI (a tool which summarises all environmental impacts into a single score - expressed in Euros) [9].

However, this tool is not without shortcomings. While the LL highly rewards the use of biobased materials in the 'material use' aspect, the environmental impact isn't always guaranteed to be positive [12]. Therefore, the LL lacks nuance to some degree.

Thus. even though progress is being made, municipalities and the playground industry are still in an infant stage when it comes to developing circular and sustainable (C&S) playground equipment (PE), as both Oost-Mulder and Vreugdenhil [13] argue that they are still at the bottom of the R-ladder (Figure 6).

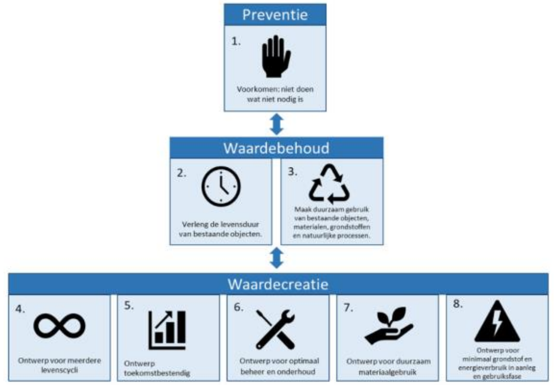


Figure 4: Leidse ladder [10]

Smarter product use and manufacture	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different function
	Rethink	Make product use more intensive (e.g. by sharing product)
	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	Reuse	Reuse by another consumer of a discarded product which is still in good condition and fulfils its original function
	Repair	Repair and maintenance of defective product so it can be used with its original function
	Refurbish	Restore an old product and bring it up to date
	Remanufacture	Use parts of a discarded product in a new product with the same function
	Repurpose	Use a discarded product or its parts in a new product with a different function
Useful application of materials	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	Recover	Incineration of materials with energy recovery

Figure 6: 10R design strategies for the Circular Economy [14].

1. Introduction

Context, assignment & research objective

In order to design PE for the Dutch CE, it is important to understand what C&S means.

Effective circular product design dictates designing for the inner loops of the Butterfly Diagram [15] (Figure 7), as this results in the highest value retention [17]. This can be achieved by designing with the 10R design strategies for the Circular Economy (Figure 6) [15,18], where the equipment and materials circulate, and waste and pollution is eliminated as much as possible [19].

Sustainable design is the practice of creating a product with the approach to minimize its environmental impact and provide economic and social benefits to its stakeholders (Triple Bottom Line (TBL)) [20,21,22]. Circular design strategies and business models are a means towards the goal 'sustainability' and should therefore create value across the TBL [18,23,24]. Bakker [18] further conclude that circularity in product design emphasises on retaining the value of materials and the created products by reusing and or recycling them as much as possible. The accompanying business models focus on preservation, with sustainability as the basis.

Both the LL and '5 strategies for circular playground design' are based on the 10R design strategies for the CE. Therefore, they served as a starting point to do research on C&S in PE.

1.3 Assignment

Van Ee Speel, a Dutch playground design and maintenance agency, wants to keep up with the developments surrounding CE and has tasked me to design circular and sustainable playground equipment, which also encourages children to play outside more. This playground equipment will be developed for the Dutch market.

The original project brief can be found in Appendix A.

1.4 Research objective

This thesis will focus on developing a design approach towards circular playground equipment, while also increasing the environmental, social (i.e. children's physical health and wellbeing) and partly economic (as the design should also be viable) benefits. The conducted research focuses on the implementation of the 10R design strategies into the design of the PE, as well as the design considerations which encourages children to play outside more.

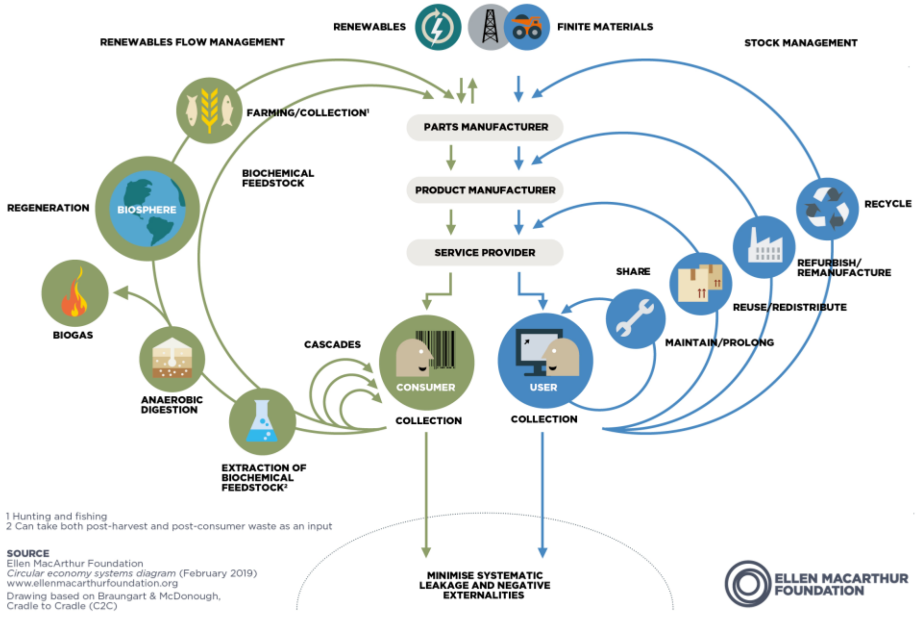


Figure 7: Butterfly model [16]

2. Method

Research question and methodology

To conclude on a design approach, needed to develop C&S PE, I formulated a research question and sub-questions. The research, conducted in this thesis, will provide the knowledge needed to answer the research question.

2.1 Research question

How can circular product design principles be effectively applied to the development of sustainable playground equipment, while the design also improves children's engagement, physical activity and well-being?

Method

Secondary data analysis, interviews with stakeholders and experts, observations and a design session with children. Thematic analysis was used to see if there was a consensus among stakeholders and experts.

The following sub-research questions were formulated to structure the research and find an answer to the research question stated above.

Sub-question 1

How have circular design principles already been implemented in product and playground equipment design, and how can design considerations increase its effectiveness?

Method 1

A gap-identification analysis was performed to find the gap between the approach of playground developers towards implementing the circular design strategies, and the possibilities which design considerations can offer in increasing effective implementation.

Stakeholder and expert interviews and secondary data analysis based on mostly academic literature was used to recover relevant knowledge on each of the 10R design strategies for the CE and potential design considerations. Thematic analysis was used to see if there was a consensus among stakeholders and experts.

Sub-question 2

How can material choice contribute to the effective implementation of the circular product design principles?

Method 2

Secondary data analysis and interviews with stakeholders and experts was used to retrieve relevant data of different materials. Thematic analysis was used to see if there was a consensus among stakeholders and experts. The methodology by He et al. [21]; 'Typical product sustainable design methodology for product life cycle', was used as a guide to find relevant information in all aspects of sustainable design throughout the life of a product.

To assess the relevant materials, a list of requirements was constructed. This list was used in a material table, where each requirement has been assigned KPIs (Key Performance Indicators) to measure the performance of each individual material and compare it with other materials based on their quantifiable material properties. The materials have been compared based on a Harris-profile.

Sub-question 3

How can design considerations, regarding PE, contribute to increased outdoor play, physical activity and wellbeing among children?

Method 3

Secondary data analysis based on mostly academic literature was used to find relevant knowledge on design considerations to increase outdoor play, physical activity and children's wellbeing, A context-mapping and design session was conducted with children aged 6-11 to acquire knowledge from the users of PE. This will be discussed further in Paragraph 2.2. A thematic analysis was used to see if there was a consensus among experts and children regarding the design of appropriate PE.

2.2 Context mapping session, design session and playtime observations with school children aged 6-11

A context mapping- and design session was conducted to conclude on which play functions and design considerations, among 6-11-year-olds, encourage children to play outside more, as the results are critical in answering sub-question 3. Furthermore, their input is of great value, as involving the users in the design process is crucial to understanding their wants and needs, which can cause a prolonged product life [15]. An observation during outside playtime was performed to conclude on the preferred activities during playtime, as well as their behaviour towards certain playground equipment. The results of the session were compared with the literature study (paragraph 6.2.3) to uncover a consensus between academics and experts (the children). The complete study can be found in Appendix B. Its results will be discussed in paragraph 6.2.3.

Session method and structure

The session is based on the overarching design partnering method 'Cooperative Inquiry', in which adults and children work together to design something new [25]. The main structure is set up by means of the 'Guidebook Your Turn for the Teacher' [26], which was provided by M. Gielen during the course Co-design and Research with children. This guidebook is based on the research project Co-design with Kids, which was requested by Dutch research organizations NRO and NOW and provides support for setting-up co-design sessions which are beneficial for both designers and the participants (children).

2. Method

Context mapping session, design session and playtime observations

This guide was especially helpful, as many examples were already focused on the design of a playground (Appendix B, Figure 93), showcasing its appropriateness in such a design session. Play function cards (Figure 8), provided by M.T.R. Hettinga [27], helped with identifying the preferred play functions of PE.

The goal of these sessions is to receive qualitative data regarding children's perception on, and behaviour towards playing outside and playing with PE. The main question the children had to answer is derived from sub-question 3 and reads: 'How can playgrounds/ playground equipment be optimized to encourage children to play outside more?'.

Several exercises will both get them more acquainted with their own view on this topic, as well as prepare them for designing solutions which encourage children to play outside more. The session consisted of five parts, of which four are based on the first two parts of the 'activities design cycle' as proposed in the 'Guidebook Your Turn for the Teacher'. Going through only the first two parts of the design cycle was recommended when doing shorter sessions of ½ to 2 hours. As the playground design should enthuse a varying group of children, a large amount of qualitative data was collected. Multiple sessions with 6 classes of children ensured that the conclusions were rich with the data of 131 children. A session plan was constructed to visually convey the structure of the session (Appendix B, Figure 94). The exercises build on the results of the previous exercises, taking the children through a logical design process step-by-step.

Before the co-design session, a context mapping session was performed to give insight into the children's world of experience [28]. Context mapping aims to create awareness of the given context by evoking emotional responses from the participants. These responses could be the participants experiences, memories, feelings or concerns regarding the context that is explored in the sessions. These sessions are based on a 'make and say' approach where the participants are encouraged to engage in creative exercises and discussions under the guidance of the researcher [29].

Data analysis method

The method used to analyse the gathered qualitative data is Reflexive Thematical Analysis, with a more latent approach [30]. The purpose of this method is to develop patterns of meaning ('themes') across a dataset that address a research question.

Implemented design strategies

As the session is most effective when the learning process is guided and promoted [31], the following design strategies were applied during the design activities.

Clarifying learning goals and success criteria
A specific learning goal is given for each exercise and discussed beforehand. This is a fruitful way to make children's participation, especially in a school context, more meaningful as they will understand better what they are learning and what the focus of the exercises are [32].

Demonstrations and practising with the aid of examples
Designing is a new activity for children. Therefore, the first two exercises will serve as a 'practice round', in which the children will get familiarized with the topic and design-thinking.

Feedback moments
After each exercise, an open discussion will be held to discuss how the exercise went and if they are ready for the next.

Research group

Children from the 5th and 6th class (8-10 years old) were selected as they are in the middle of the group of children that would play with playground equipment (4-12 years old). Furthermore, this age group can understand the tasks given to them and provide creative solutions as they are capable of creative thinking [33]. A design session was also conducted with a group of children from the 3rd (age 6) and 7th (age 11) class to see if there is a difference between age groups.

Informed consent

P. Jakobs has authorized to use the collected data and images as long as it is only used in the research as provided in this thesis and the children are unrecognisable [34].

Figure 8: 6 themes of play function cards [27]

3.1 What is playground equipment?

Playground equipment started to exist in the 1900s, with a big increase in the nineteen-twenties and thirties [35] and has undergone some significant changes (Figure 9 & 10), mainly due to the implementation of the 'Warenwetbesluit Attractie- en Speeltoestellen' (WAS) in 1996 [38]. Due to this act, playgrounds became much saver but, according to several experts, also more 'boring' [4,5,39 (Appendix C.1),40].

Playground equipment can take on many shapes and consist of a plethora of different play elements like swings, monkey bars and slides, and are often made from wood, steel and plastics [41,42 (Appendix C.2)].

Well-designed playground equipment which encourages children to play outside is important because outdoor play is crucial for children's mental and physical well-being. It is linked to improved motor development, lower obesity rates, better impulse control, reduced stress and depression, and the promotion of curiosity, creativity, and critical thinking. Playgrounds are therefore not just a place to play but also to socialize [1].

3.2 Life(-cycle) of playground equipment

To conclude on an effective approach towards the implementation of the circular design principles in PE design, it is important to have an understanding of the life (-cycles) of PE, and what can be improved. Therefore, research was conducted on this topic, and a conclusion can be formulated based on stakeholder interviews.

The average life of playground equipment is 16-20 years [41,42], after which the initial lifespan (staying on the same location) is reached. Figure 11 shows the lifetime and potential cycles of playground equipment (detailed information on the lifetime was provided by A. van Ee). As can be seen in Figure 11, all phases of the lifetime of PE, from design to end-of-life, influence its success in the CE. The main issues of the playground life are maintenance, repairability and end-of-life [42,43,44 (Appendix C.3),45 (Appendix C.4),46 (Appendix C.5)].

The main problem during maintenance is that the equipment consists of many different parts which all need to be disassembled before maintenance can be done. Repairing playgrounds is sometimes also difficult, as repairs on plastic and wooden parts are difficult to perform [41].

The main problem during end-of-life is the demolition. Currently, often demolishers are in charge of removing playgrounds, which results in playgrounds being damaged and sold for its materials rather than being reused [43,45].

I will discuss these problems further in paragraph 3.5 and 3.6.

Figure 9: Playground early 20th century [36]

Figure 10: Playground 21st century [37]

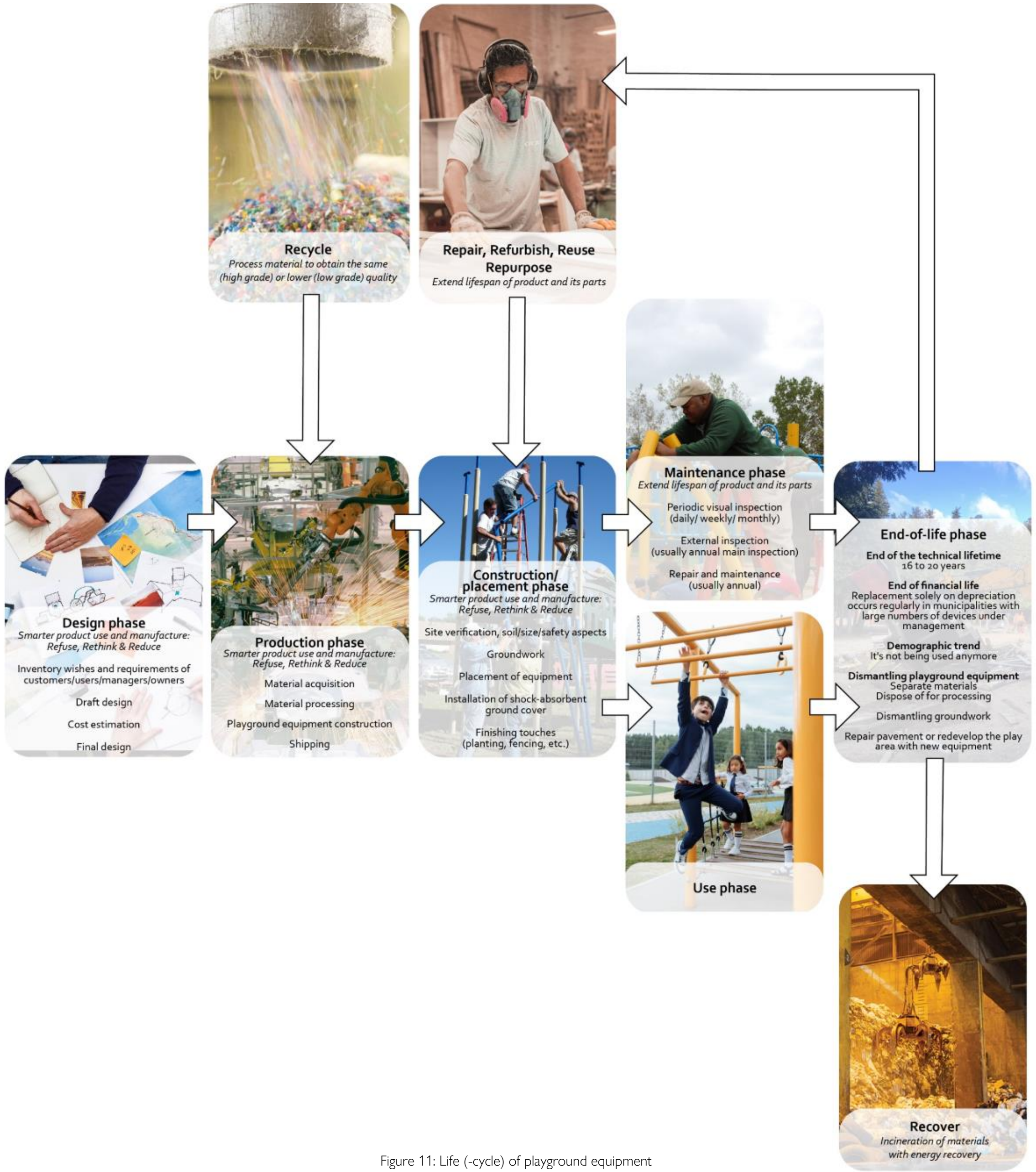


Figure 11: Life (-cycle) of playground equipment

3.3 Smarter product use and manufacture | Refuse, rethink & reduce (R3A)

Refuse, Rethink & Reduce are important steps in the 10R ladder, as these strategies can create significant environmental benefits, such as reducing material use. In this paragraph, refuse, rethink & reduce, regarding PE, have been examined, and I extracted the relevant design considerations. I have provided definitions of these principles to familiarize the reader of this thesis with these terms.

Refuse

Refuse refers to making a product redundant by discarding its specific function or by providing this same function with something completely different. Refuse also focusses on the use (or the redundance) of certain materials and production processes to create more circularity [47].

Rethink

Rethink focusses on increasing the use of a product. This can be done by providing multi-functionality or sharing possibilities. However, Rethink has a broader connotation as it focusses on the reconceptualization of processes, use and post use of products. This includes dematerialisation (the substitution of the product with a nonmaterial alternative with the same functionality) which is a fundamental component of the CE [47].

Reduce

Reduce encourages to use fewer resources, such as raw materials and energy, which in turn decreases waste. However, it also focusses on decreasing the number of produced products, for example by sharing or reusing. Also, reduce can sometimes be defined as a less drastic version of refuse, as it for example 'refuses' a part of the produced products [47].

3.3.1 (Effective) implementation of R3A in playground equipment

The circular design strategy 'rethink' is used by playground developers to come up with smart solutions to decrease material use. Nijha, for example, utilizes a 'closed soil balance' approach, eliminating the need for new soil or sand [48] through clever management of height differences and existing soil bodies [49]. With the existing soil they create small hills or pits for children to play in, creating a natural playground without the need for PE. Furthermore, they combine functions of equipment, providing children with the possibility to play with the equipment in their own way, thus reducing the number of elements needed in a playground [48].

Rethink can also be found in the design of PE. For example, parts can be simplified to fulfil the same function, like using open slots (Figure 12) instead of extra grips (Figure 13) to reduce the number of parts, and often also the mix of different materials. Likewise, a multi-material bench (Figure 14) can be replaced with a mono-material one (Figure 15) to reduce material diversity.

Encouraging children's imagination is a powerful way to rethink and reduce, as each child can find their own play value within the same playground and could result in more extensive use. Kids can play with a simple stick, transforming it into various objects like pistols, swords, or wands. The 'Blade made playground' by Superuse from 2009 embraced this idea, allowing children to freely imagine their play scenarios: "The abstract shape of the blades gives children the freedom to imagine where and what they are playing. One time they are pirates on a ship, another time princesses in a castle or rabbits in a burrow. Appealing to children's creativity is one of the best things this playground does" [54]. Playgrounds are a great place for children to engage in imaginative play, as these designated play environments encourage them to use their imagination. Playgrounds are also a great place to make friends, which often encourages imaginative play [55].

Lastly, refuse is utilized by thinking of ways to incorporate nature and natural processes in playgrounds, which eliminates the need for new resources. For example, M.T.R. Hettinga [56] imagines a playground without any new materials: "Instead of a goal, two trees can be used as a target, or by applying markings instead of placing a target you consume fewer resources (refuse on the R-ladder)". 'OBB speelruimte specialisten' has envisioned a way to incorporate rainwater into their playgrounds [57] (Figure 16). By doing this, you create a new and exciting way of playing without the need for actual equipment.

However, playground developers are sometimes also inhibited in their sustainable developments. As was concluded by Oost-Mulder & Van Weert [4], adult clients are quick to opt for designs with many devices in them, without looking at the quality or durability. Out of necessity, suppliers therefore offer designs with several cheap devices instead of a few more expensive ones. As a result, the playground equipment is often not exciting or challenging for children. Therefore, Oost-Mulder & Van Weert [4] recommend to move towards less equipment while increasing play value with circularly responsible equipment.

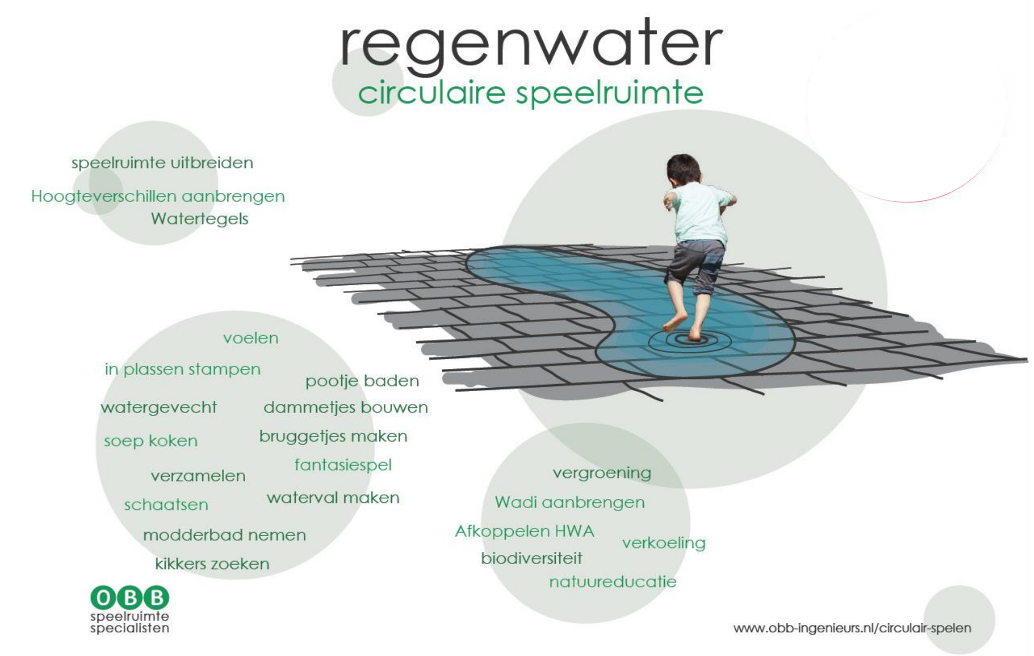


Figure 16: Regenwater circulaire speelruimte [58]

Figure 15: Wood bench with log legs [53]

Figure 14: Bank C-vorm ([52]

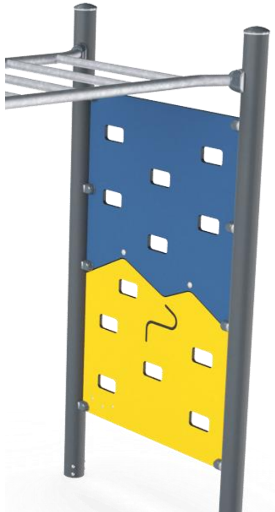


Figure 12: Klimtoestel - Uno [50]

Figure 13: Robinia Kasteel S [51]

3.4 Extend lifespan of product and its parts | Durability (maintain & prolong)

Durability is not an official step in the 10R design strategies for the CE. However, it is an important part of products to become applicable in the CE [59], as it extends the lifetime of a product, thus facilitating reuse [60]. In this paragraph, durability, regarding PE, has been examined, and relevant design considerations have been extracted. I again provided a definition to familiarize the reader of this thesis with this term.

Durability

Durability in products is its ability to withstand (un-)expected conditions throughout its life(-cycles) [61]. Durable products often have a longer initial lifetime, which maximizes the retention of value (prevents early disposal with landfilling or recycling requiring additional energy and carbon emissions), delays the need for new products, enables reuse and minimizes resource depletion [60]. Because of this, the product's total environmental impact is reduced across its lifecycle [62].

There are several reasons for PE to become obsolete:

- End of the technical lifetime (16 to 20 years) [63].
- End of financial life (replacement solely on depreciation occurs regularly in municipalities with large numbers of devices under management, Leiden is one of these municipalities) [63].
- Demographic trends [63]. Oost-Mulder & Van Weert [4] confirm this last reason, stating that in practice, there is a need cycle of about 7 years for play space. Children are then a target group older, and residents leave or move into the neighbourhood.

3.4.1 Implementation of durability in playground equipment

Durability has mainly been implemented by means of offering 'durable' materials, which can endure different weather conditions and extensive use.

Playdale, a UK-based company with an exclusive contract with Van Ee in the Netherlands [46], develops durable playground equipment components made from wood, steel, and composites. These parts are certified to meet specific safety standards, such as the BSEN1176 safety standard (European Safety Standards for outdoor PE). Playdale also considers material performance and follows material suppliers' guidance for warranties [64]. Van Ee noted that Playdale typically offers a 10–15-year warranty, based on years of experience and material durability [41].

Kompan produces playground equipment made from durable Robinia wood, which they claim is a very strong and long-lasting material, which makes for durable playgrounds which are close to maintenance free and able to last for many years [65].

3.4.2 (Effective) methods to implement durability into (PE) design

Besides considering a durable material, several other methods can contribute to the effective implementation of durability in PE.

Considering the surrounding material and designing for minimal wear and tear can postpone early obsolescence. For example, for a wooden playground, it is important to consider the underground. Putting it on a sandy substrate results in sandy feet causing accelerated abrasions to the wood [45].

When choosing a material, it is important to know how it behaves under changing circumstances (cold, heat, moist, etc.). Wood for example, can expand and shrink, which could weaken connecting joints over time if this was not thought of during the design. This could cause weakness in the overall structure which increases early disposal and is not safe for children to play on [66 (Appendix C.6)]. Therefore, the material behaviour should be considered.

All products age, and therefore often change in appearance. Especially those that are mostly used outside, such as PE. This change in appearance is commonly perceived as damage or degradation, which for many products contribute to premature disposal and therefore short product lifetimes [67]. However, Lilley et al. [67] suggest to consider the material change during the design phase in tandem with a products form, use and ergonomics to guide products into sustainable patterns of use, care, maintenance and reuse. Therefore, it is important to understand how the chosen materials change overtime and design with this in mind (design for aging), as this can postpone early obsolescence.

Designing for 'emotional durability' can prolong the life of a product as an emotional bond between a product and its user can positively influence the tendency to retain the products for longer. This can be achieved by allowing the users to personalize/ customize their products [68].

Besides personalisation/ customization, several other design strategies can contribute to extending the life of a product: upgradability, modularity and adaptability [15]. These strategies, together with personalisation/ customization will be discussed in the following paragraphs.

Upgradability

Upgradability of products can be defined as improving its functionality and capability in order to extend its useful life. This is achieved by maximizing the products ability to change its functions over time, according to the changing wants and needs of its users, while staying almost the same in terms of form or structure. No new product is needed, but only the components that are obsolete are replaced. This delays early unnecessary replacement, thereby reducing resource consumption and waste [69].

However, even though product upgrade can facilitate several environmental benefits, it is underdeveloped in the market and only considered in a theoretical fashion [69,70]. Even so, based on theoretical research, upgradable products do not guarantee a viable business model in terms of financial performance [71]. However, Zikopulos [72] concludes that upgradability should not be evaluated on its economic performance, as the goal of implementing this strategy is to promote the CE principles. Therefore, in a theoretical fashion it could be valuable to implement upgradability in PE.

As is the case in other consumer markets, upgradability in playground equipment is rarely applied. 'Upgrading' in this context is often used as a term to talk about making an old playground (which is often not made by the company that 'upgrades' it) better, or even replacing it:: "The city of Herford had set itself the task of gradually 'upgrading' its public playgrounds. These playgrounds have been revised and partly replaced" [73], which is not what is meant by upgrading a PE in the context of this thesis.

As was concluded by van den Berge et al. [70], to apply the beneficial aspects of upgradability in product design, product-service systems and modular design (i.e. products consisting of various interchangeable modules), which have already been applied by PE developers, should be implemented.

Personalisation/ customizability

Product customization enables customers to personalize/ customize a product according to their specific needs and preferences [74]. For example, customers can be offered to choose between several colour schemes or different PE modules, to provide them with a 'unique' playground. However, it is also possible to provide customers with a completely unique playground, which is designed and built from scratch.

Personalisation is considered to be an approach for prolonging the value lifetime of a product and minimizing resource input [75] as it can stimulate retention via product attachment, which increases the willingness of users to repair and maintain their product resulting in a longer lifetime. People can also develop irreplaceable attachments to products that express their identity. Such self-expression can be triggered via product personalisation [70]. In this regard, its approach to the product-user relationship is similar to 'emotional durability' [68]. Therefore, to postpone early obsolescence, the buyers or users of PE should be able to customize their playground to their specific needs.

Playground customization has already been widely offered by playground developers. Here, 'customization' mainly implies the option to design a playground based on the wishes of the customer. Kompan for example offers its customers one-of-a-kind playgrounds which are custom designed and build by them (Figure 17). Changing (part of) the PE after the initial placement is not offered by many playground developers. However, this could be an interesting approach to keep the users of the PE interested and invested.

To further implement personalisation into PE, a modularization strategy could be used to facilitate companies' needs for developing customized products in an efficient way, to fulfil specific customer needs [77].

Figure 17: From design to custom playground [76]

Modularity

Modular design enables product features to be grouped within the product, which facilitates interchangeability, accessibility, disassembly and removability of these sub-assemblies. Modularity therefore allows for more efficient repairs, and the recovery of its components at its end-of-life, therefore enabling effective recycling [78].

Modularity offers significant benefits throughout the lifecycles of a product, as was found by Sonego et al. [79] and Machado & Morioka [80] (Table 1). Therefore, implementation of modularity in PE would be beneficial, which has already been done by several PE developers from all over the world, showing its potential in the PE market.

Playground centre (New Zealand & Australia) developed the 'Modular Active Play Systems' which allows users to choose from different modules which can be joined together. Furthermore, components can be added and changed down the track [81].

Sterling West (United states) also developed modular PE where they describe a modular play system as 'a group of modules that fit together to form various sizes, shapes, challenges, and accessibility' [82], where you can 'develop a configuration that will fit specifically in your space for your intended audience' [82].

Simplified playgrounds (Canada) developed PE which children can configurate themselves, called the 'Goldfish Kit'. These pieces can provide open-ended, interactive, and inclusive play opportunities [83]. This approach is interesting but less effective in public spaces, as the elements can be easily moved or stolen.

Novum (Netherlands) also developed a modular playground called 'MPfP' (Modular Platform for Playgrounds), which creates many benefits: "Assembly can be achieved in one day, possibility of easy relocation in the future, reduces installation costs, reduces construction costs, possible repairs include the rapid replacement of modules" [84].

Lastly, Ijslander (Netherlands) and the municipality of Rotterdam [45] developed 'Click & Play', which offers 3 different 'Building blocks' that all serve different play needs, such as the base of a swing, a slide, a turning seat, a climbing element, etc. [85] (Figure 18).

Table 1: Benefits of modular design

Topic	Benefit	Source
Material	Reduces waste in the production process, therefore using the raw material to its full potential	[80]
	Reusing modules avoids the production of virgin components	[79]
	Fewer material types	
	Material compatibility	
Product variety	It increases product variety as it offers more choices	
Supply chain	Reduces emissions of CO2 as it minimizes transport and product obsolescence, thus it decreases incineration and landfill processes.	[80]
	More efficient transport and storage due to the reduction of the number and size of shipments	[79]
Manufacture	Reduces manufacturing and assembly time of the final product	[80]
	Minimizes energy usage throughout a product's life	
	Increased feasibility of component/product change	[79]
Obsolescence	Provides greater product durability	[80]
	Modules can be designed to be introduced into existing structures, allowing for innovation, redesign and continuous change	
	A modular product provides flexibility, allowing different uses during its lifecycles and the possibility of dismantling and reassembling components, considering the multifunctionality	
	Usage life compatibility	[79]
	Accommodate future uncertainty	
	The purpose of modularity is to gain flexibility for mass customization. Furthermore, flexibility means more product variations, room for environmental improvement, and changing of modules without difficult changes to the rest of the system	
	Modular product design affects product innovation from vantage points of marketing and technology development	
Maintenance	Maintenance involves preventive and recovery repairs. By offering product modularity, the individual modules can be easily replaced	[80]
	Simplified maintenance	[79]
	Reduce maintenance costs	
	Speeds up maintenance	
Repairability	Ease of repair	
	Improve repair quality	
Upgrades	A modular product meets a common interest in Upgradability, facilitating the separation, exchange and insertion of the relevant components	[80]
	Fosters upgrade, adaptation and modification	[79]
	Promote continuity	
Functionality	Expand functionality	
Recycling	Modular product components that still have useful properties can be reprocessed and may have different lifetimes	[80]
	Product modularity reduces the difficulty of disassembly as the product modules can be more easily separated	
	Easy disassembly for recycle	[79]
Reuse	A modular design can increase repeated use of components, allowing for reuse	[80]
	Easy disassembly for reuse	[79]
Remanufacture	With modular structures, the remanufacturing process becomes simpler and consists of restoring products at the end of their lifecycle	[80]
	Remanufacture simpler due to functional independence	[79]
Economic	Generates revenue from remanufacturing and recycling	[80]
	Cost reduction due to manufacturing, repair and recovery	

3. Theoretical framework

Implementation of circular design principles in playground equipment design

Adaptability

Adaptability in design allows a product to stay relevant throughout its lifecycles, thus avoiding obsolescence. To enable this, adaptable products anticipates and enable changes and adjustments that might be made to it throughout its use cycles [78].

Adaptability is already implemented in the building sector [87], which shares many similarities with playground equipment in terms of material use and (dis-)assembly practices, as was concluded by Oost-Mulder & Van Weert [4]: "For playgrounds, we do not need to invent something new, but can hitch a ride with construction (of buildings), which as a major resource user is busy with new circular ways. This is also where all the material types we are familiar with for playgrounds come into play".

Dams et al. [87] define 'designing for adaptability' in the building sector as "design which allows for reconfiguration or conversion to reflect changes in the purpose or use of a building during the design life of the structure, minimising the risk of demolition as a result of economic, societal or functional obsolescence". This is in line with the reasons for playground demolition, which further shows the appropriateness to look at the building sector to conclude on the effectiveness of adaptability in PE design.

In the study from Dams et al. [87], it was concluded that structures which possessed higher adaptability also had lengthier useful lives and thus took longer to become obsolete. Hamida et al. [88] further concluded on the benefits of adaptability in buildings, stating that adaptability in buildings is fundamental for implementing CE in these kind of structures as most of the circularity determinants interrelate with the determinants of building adaptability. Hamida et al.'s research is relevant, as they relate adaptability not only to the building sector but discuss it in a wider context by focussing on design related determinants, such as dismantlability, removability, recyclability and modularity.

Hamida et al. [88] also provide several 'adaptability strategies', two of which are relevant to PE design: configuration flexibility and material reversibility.

Configuration flexibility

Configuration flexibility is the possibility to reconfigure the layout of components without using external resources or generating waste, which can be achieved by using demountable and movable components [88]. Such products, which can be disassembled, and some parts can be reused, are more likely to contribute to the Circular Economy [89].

Material reversibility

Material reversibility is the possibility to provide, use and reuse building materials as efficient as possible, which can be achieved by using secondary materials, applying material passports, and reusing discarded materials [88].

By designing adaptable products, you can cater for the different expectations and needs of its users throughout its multiple lives [90], which is in line with conclusions from Oost-Mulder & Van Weert [4] (7 year need cycle), Hainess-Gadd et al. [68], Khan et al. [69] and Van den Berge et al. [70],

As partly discussed, Ijslander has developed 'Click & Play'. This PE fulfils many of the design principles such as modularity, adaptability and interchangeability, as the design of the play modules allows for providing different play needs, which can be changed according to the needs and preferences of its user. The modules can be easily disassembled from its base and interchanged with other modules.

Furthermore, adaptability is in line with the LL as points can be earned by developing demountable PE, which can be reused [91].

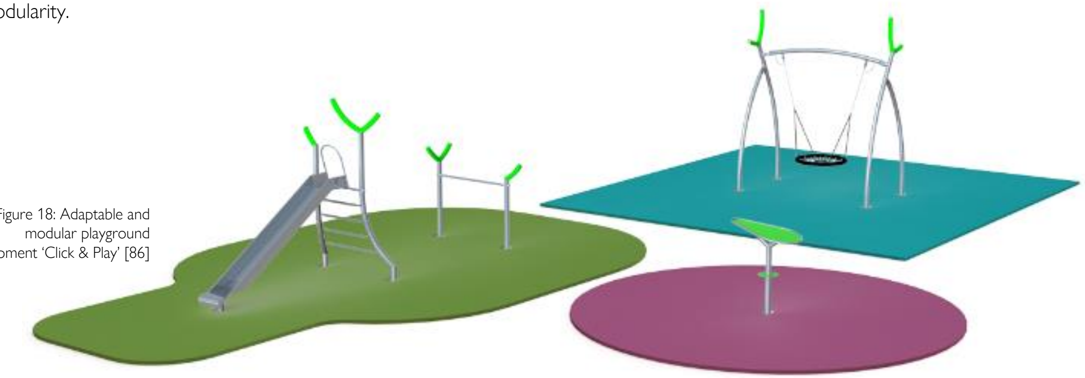


Figure 18: Adaptable and modular playground equipment 'Click & Play' [86]

3.5 Extend lifespan of product and its parts | Reuse

Reuse can be defined as the further use of a product by a different user, as it is still in good condition and fulfils its original function [47].

Reuse of the PE, after its initial lifetime, is discussed in this paragraph. Reuse of materials or objects to be used in the proposed PE design is discussed in paragraph 4.3.

Allowing interested parties to reuse products, instead of having to produce new ones, provides significant environmental benefits. Firstly, it extends the life of these existing products, decreasing the demand for new resources, such as materials, to be extracted and processed into a new product. This in turn lowers emissions and energy consumption from manufacturing facilities. When less new products are produced and most of them are reused, the amount of them ending up on landfills is also reduced. Lastly, as natural resources play a crucial role in ecosystem health, reducing the demand for, for example new wood, prevents the destruction of wildlife and nature [92].

3.5.1 Implementation of reuse in playground equipment

Reuse of 'old' playground equipment on site or by means of 'playground depots' [45,93 (Appendix C.7)] is done by companies like Nijha [48], which reduces the need for newly produced PE. Van Ee Speel also reuses some equipment on site [94]. They mainly reuse PE which is still technically sound, but they are not specifically designed for reuse.

3.5.2 (Effective) methods to implement reuse into (PE) design

Implementing a product-service system (PSS)

A PSS is a model where the equipment remains the property of the supplier. The equipment or playground is provided as a service rather than a product, with the supplier providing maintenance, management and possibly the use of the playground [95]. The customer subscribes for renting the product, in this case the PE, and if the user wants to return it, the producer can retrieve it and reuse some parts or materials into building the product again [89]. Such a PSS model is still new within the PE sector [95].

As was discussed in paragraph 3.4.2, a PSS can contribute to the effective implementation of the upgradability, adaptability, personalisation and modularity design strategies, and is therefore an interesting approach towards implementation of the circular design principles. Furthermore, it can also create several environmental benefits.

Firstly, a PSS is a way of reducing consumption (of raw materials) through alternative possibilities of product use, which include closing the material cycles and increasing dematerialisation. By reusing products in a PSS, waste streams will also be decreased [96].

Furthermore, a PSS business model provides opportunities to achieve a competitive advantage and provide a system through which products can be efficiently retrieved to be reused or, if the product can no longer fulfil its function, recycled [69].

Several drawbacks of a PSS have been expressed by van Ee [97 (Appendix C.8)]:

- It requires the playground administrator to perform daily checks which is costly: "The playground administrator is responsible for the safety, which cannot be guaranteed to such an extent. It would mean that an administrator needs to personally check their playgrounds almost every day. Now, a teacher or concierge does a daily check, but this would not suffice in a PSS". Den Dulk [44] confirms this: "Renting for example would be difficult as there may be an issue about ownership if an accident occurs. Less involvement can be felt by the municipality and responsibility can often be shifted away."
- Due to municipal competitions, offering reused playground equipment is a financial risk: "Municipalities host competitions where companies pitch playground ideas. Offering affordable solutions with reused equipment is a risk, as transport damage and rot can cause unexpected repair or replacement costs not factored into the initial price".
- As playground equipment (in the current business model) stays in the same place for +-20 years, rotation is not efficient and therefore not profitable: "It is not profitable to supply old playgrounds as the rotation would take too long".

Many of these drawbacks are related to the behaviour of the municipality towards a PSS. However, as was concluded from the municipal meeting on the 15th of August [98], the municipality of Leiden is working towards a more circular approach (also by means of the Leidse Ladder) and they have an open mind towards these circular models.

Neat dismantling instead of conventional demolition

The reusability of PE is hindered by inefficient (conventional) demolition (Figure 19), which in turn causes more equipment to end up on landfills. The main problem of Conventional Demolition (CD) is that it prioritizes cost savings over reusability [100].

Currently, due to the municipality being stuck with a contract that dictates that the contractor is responsible for removing the old playground, demolishers are in charge of removing playgrounds. This is often done with cost-saving as the main motivation, which results in contractors hiring demolishers with no knowledge of demolishing PE. A lot is pulled straight out of the ground, as demolishers don't benefit much from pulling it apart neatly as it takes more time and money, which means it cannot be reused [45]. Roubos (technical consultant play municipality of Rotterdam) therefore encourages contractors to dispose of their PE themselves and do this properly.

This problem is also confirmed by van de Minkelis [43], as he states that demolishers typically aim to minimize expenses since their payment is fixed, regardless of reusing materials. It often results in materials being dislodged with a crane and sent to landfills, incurring disposal costs, with only some materials being recycled or incinerated.

Neat dismantling of the various components by the contractor could solve the issue of inefficient demolition (Figure 20) [45,102]. This is already done by Leiden, as van Delft [103] indicates, that they are the first municipality, since 2022, to carry out a circular demolition policy in projects where they are the client. Materials released from demolition and preparation for construction in other building projects, both inside and outside the municipality, are reused in the highest possible quality. Besides reducing construction waste and demand for new materials, this way of working also contributes to reducing CO2 emissions.

Figure 19: Conventional playground demolition [99]

Figure 20: Neat playground dismantling [101]

3.6 Extend lifespan of product and its parts | Repair & maintenance (R&M)

Repair can be defined as repair/ maintenance of a defective product so that it can be used with its original function [18], with 'design for maintenance' being a strategy which aims to reduce the difficulties and costs associated with maintaining products [104].

Effective repair and maintenance of PE is crucial, as it can prolong the life of the PE, keep children safe and improve the overall play experience. If playground equipment is broken or unusable children will miss out on opportunities to play [105].

3.6.1 Implementation of R&M in playground equipment

Many companies/ organisations offer services to repair playground equipment on site. For example, Playground guardian offers RENEW, which includes "deep cleaning, replacing and repairing, painting and recoating decks, platforms and steps" [106].

DZB Leiden repairs municipal structures, including playgrounds, and employs people with a distance to the labour market to do so [66]. However, DZB Leiden is employed less and less by the municipality due to budget cuts: "We used to do this a lot but are doing this less and less because it is cheaper to buy new playground equipment. Because of this we don't perform the same extensive repairs as we used to. A main reason is the changing demand from the municipality, where there is a difference between the policy- and the executive department. Playground repair would be a good initiative towards circularity, but often there is just no budget" [66]. This again highlights the influence municipalities have on the success of circular playgrounds.

A. Van Ee offers maintenance as an overall service when providing its customers with a playground. The following can be concluded based on his experience [41]:

- Repairs and maintenance are performed yearly. Regular wear occurs every ¾ years, with the main issues being faulty cables or bolt connections.
- External inspections are performed once a year by an official.
- Visual inspections and small repairs, like tightening screws, are performed daily by teachers or concierges.
- The lack of design for easy (dis-)assembly causes problems during maintenance. This is mainly due to equipment consisting of too many parts.

3.6.2 (Effective) methods to implement R&M into (PE) design

There are several ways to optimize the design of the PE to make it more suitable for maintenance and repairs.

When considering materials and the shape and structure of the PE, simultaneously consider how this will affect the maintenance procedures. For example, while wooden equipment should be inspected for rot or splinters, metal equipment should be checked for rust. On the other hand, plastic equipment should be inspected for cracks and breakage. Some types of equipment will have components that require particular attention due to possible risks, which includes swing chains and seats, anything with moving parts, and equipment with steps [107]. Making choices which decrease needed maintenance in turn reduces energy use and carbon emissions.

Secondly, smart mono-material connections, instead of using additional bolt connections, between parts could simplify maintenance if the design allows for this, as well as reduce the number of parts and materials needed [66].

Lastly, establishing 'participation in maintenance' can create a feeling of togetherness, facilitate Social Return and speed up the maintenance process.

Oost-Mulder & Van Weert, [4] propose to involve residents into the maintenance of the playground, as one of their 5 points of participation is to ask "What do you yourself contribute to additional required maintenance or monitoring in the coming years?". As is confirmed by Rook, Play technician at the municipality of Almere, residents are eager to help with maintenance. They are often involved in the maintenance procedures of municipal playgrounds and help out as doing this themselves is much more efficient than having to wait on the municipality [108].

Organisations like DZB Leiden employ people with a distance from the labour market, who perform smaller maintenance jobs on playground equipment [66]. During the municipal meeting on the 15th of August [98], an interest was expressed to work more with organisations like DZB, which would facilitate Social Return.

3. Theoretical framework

Implementation of circular design principles in playground equipment design

3.7 Extend lifespan of product and its parts | Refurbish, remanufacture & repurpose (R3B)

Repurpose

Repurpose can be defined as using a discarded product, or part of its components, into a new product with a different function. Furthermore, it also means reusing a product for a different purpose, which is often referred to as 'open-loop reuse' [47].

Remanufacture

Remanufacture implies reusing discarded components of a product into a new product with the same function. Important to note here is that a remanufactured product should have the quality of a brand new one. Therefore, it is different from repurpose, refurbish or reuse [47].

Refurbish

By refurbishing a product, it is restored and brought up to date, which allows it to be used again. It often involves the repair or replacement of parts of a product [47].

3.7.1 Implementation of R3B in playground equipment

Refurbishing playgrounds is already implemented in the playground market. Several PE companies offer refurbishing services and refurbished equipment.

Nijha refurbishes PE by offering a Playcycle-certificate. A device with a playcycle certificate is sold for the duration of 5 or 10 years. After this term, the equipment is taken back to be refurbished which allows it to be used again. If the equipment is taken back after 5 years, the buyer gets 30% of the purchase value back. After 10 years, the buyer gets 10% back [4].

Playground depots also offer refurbished PE. Roubos, manager of the playground depot in Rotterdam, sees opportunities as he explains that parts of PE can be used for repairs and complement existing and new playgrounds. Certain play elements, such as skate elements can still be used perfectly in another place, "perhaps with a different function" [109].

However, Roubos [45] also explains that there are several difficulties surrounding the depot. For example, specific PE is reserved by interested parties. However, after a few weeks he often never hears back from these people. Because of this, they have set a 3-month deadline on reserving parts. Furthermore, Roubos stated that keeping an updated list of everything that comes and goes is difficult. The reasons for this is that a wide range of people work irregular shifts, the depot is a large, but with limited supervision, area and therefore equipment gets 'stolen'. Lastly, as they only repair/ refurbish play elements when there is an interested party (Rotterdam pays for the repairs), most of the parts that they have looks dated or damaged, which is not attractive for potential customers.

Repurpose is also used in playground design, mostly in terms of reusing 'waste' and giving it an alternative play purpose (this will also be discussed further in paragraph 4.3). For example, Boerplay developed a playground in Leiden in 2021 with repurpose in mind. Waste materials such as wheels and a sewer pipe were integrated into the playground and could be used to play on and in [110].

Remanufacturing of PE is not applied. Even so, it is not common practice in any industry, even though the engineering knowledge on how to design products to fit the remanufacturing process is widely reported in literature [111]. Furthermore, even though it is not common practice, remanufacturing can facilitate several environmental benefits, as it avoids the use for new materials, similar to 'product upgrade', and thus energy consumption and carbon emissions [111].

3.7.2 (Effective) methods to implement R3B into (PE) design

As was concluded by Oost-Mulder & Van Weert [4], while adult clients demand playgrounds with much equipment, the focus should actually be on offering less equipment with more play value. In order to do this, a designer should look at play functions rather than playground equipment, i.e. sliding instead of 'a slide'. This creates room for smart solutions which minimizes the need for new PE or materials, as was expressed by Roubos [109]: "I want to convince designers to stop thinking from the device itself. People still think too much about the picture, while reasoning from the function of a device is much more important. A play-need like swinging can be filled with different kinds of equipment. It doesn't necessarily have to be a swing. If playgrounds are designed from this philosophy, it creates more opportunities for reusing equipment and materials. This method also gives designers more freedom". The 'play function cards', as described in paragraph 2.2, can help establish the desired play functions, for which several PE designs can be the solution.

3.8 Useful application of materials | Recycle

By recycling a product, it is transformed into its basic materials or substances, which can then be reprocessed to create new products. The embedded value of a product such as the invested time and energy to produce the product is lost, but the value of its materials is retained to some degree. Therefore, it is an important step for all products in the technical cycle of the Butterfly diagram [17].

As incineration of products for energy recovery or discarding them on landfills is not a preferred end-of-life approach, recycling of the materials should therefore, if possible, always be applied at the end of a products life. However, even though recycling is an important step in the CE, the loss of embedded labour and energy and the need for new raw materials and production to remake products entirely, mean that it is a lower value process compared to reuse or remanufacturing [19]. Therefore, recycling is an important step towards circularity, but should be performed at the end of a products life, preferably after several reuse cycles.

Therefore, it is more important to look at reusing the equipment, rather than recycling, as this results in more environmental benefits, as was concluded by Minunno et al. [112] in a study where they compared both the reuse and recycling of parts of a modular house. The results of this research are relevant as PE and houses make use of the same kind of materials and are similar in some of their (dis-) assembly practises, as was also stated by Oost-Mulder & Van Weert [4]. Minunno et al. [112] conclude that in a building context, reuse is a more beneficial practice toward a CE when compared to recycling as it offsets greenhouse gas emissions while also benefiting several other tested environmental indicators. Furthermore, it is suggested that recycling is the least beneficial of the 3R's (reduce, reuse, recycle), as some recyclable materials are invariably wasted or contaminated in the process [112].

3.8.1 Implementation of recycle in playground equipment

Playground developing company Lappset is aware of the importance of PE recycling and argues that all the parts of the Lappset equipment can be recycled or are otherwise used to generate energy [113]. They furthermore provide their clients with a list of 'general recycling instructions' for each of the different materials of the equipment.

However, after conducting further research on the recycling of playground equipment, not much could be found, except for equipment that was made of recycled materials. However, a clear end-of-life plan is needed in order to retain as much value from the equipment and its materials as possible.

3.8.2 (Effective) methods to implement recycling into (PE) design

Recycling of the PE should be considered as the final resort and implemented only after several lifecycles. However, finding a way to effectively recycle the equipment at its definite end-of-life is still an important step towards circularity, in order to retain the remaining value of a product and its materials (as opposed to incineration for energy generation or discarding it on the landfill). This can be done by designing for easy disassembly (Figure 21) [114], which allows the different parts of the PE to be separated into their basic materials and recycled accordingly. Furthermore, a material should be chosen which can efficiently be recycled, with recycling taking place in the Netherlands and resulting in low energy use and carbon emissions.

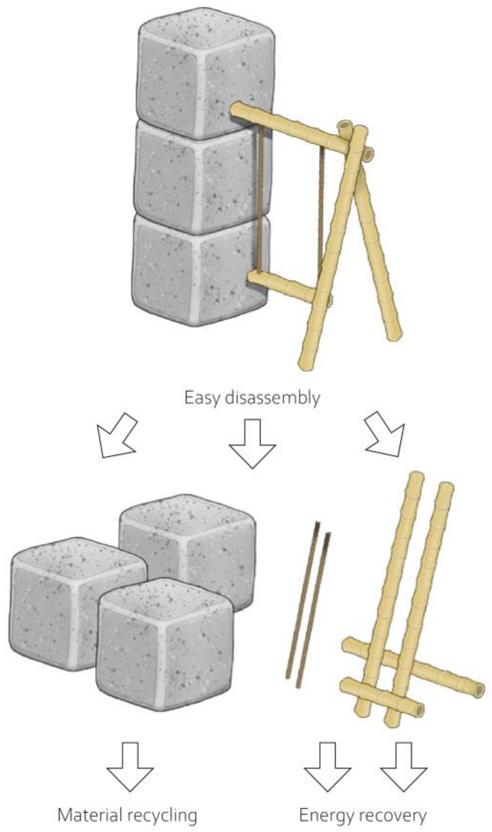


Figure 21: Easy disassembly of the PE

Material choice is an important aspect of design in general, as it influences several facets of a product, such as production, its durability, recycling, reuse, among others. Therefore, material choice is important for the effective implementation of the circular design principles. For this reason, research was performed on several potential materials, which could be used for the PE.

A list of requirements has been set-up (paragraph 4.1), which is partly based on insights derived from the secondary data analysis as can be found in Chapter 3, results from research performed by He et al. [21], Janjua et al. [115] and Neri et al. [116] and my own considerations. The list of requirements is used to gather relevant material information for each individual material, as well as compare them amongst each other.

To make a clear overview of each materials data, I constructed a table, which can be found in Appendix D.1. Here, most of the requirements have been assigned Key Performance Indicators [116] to more effectively measure the performance of a material and compare it with other materials based on their quantifiable material properties, which are mostly retrieved from Granta Edupack 2023. The structure of the table is loosely based on a Harris Profile (derived from the Dutch Design Guide), as it graphically represents the strengths and weaknesses of the material with respect to the predefined design requirements [117]. This further allowed for efficient comparing between the examined materials.

To comply with the environmental requirement 'The material must be recycled, and/or biobased and/or derived from reuse' the following topics were investigated: Reusing refurbished PE, reusing 'waste'/ materials from other industries, using recycled materials and using renewable biobased materials. The pre-selected materials discussed are based on their: Pre-existence in current PE, promising developments in terms of sustainability, circular possibilities (reusing or recycling a 'waste' stream and recycling at the end-of-life) and form-freedom (allows to make interesting equipment from a mono-material).

To delineate the scope of this project, the Netherlands is chosen as the country to design for/in. Because of this, conclusions on material acquisition, transport, manufacturing and recycling are based on their possibilities within the Netherlands. Retrieving materials from the Netherlands and processing them here results in a lower carbon footprint as a result of minimized transport, when compared to doing this in countries oversees.

4.1 List of requirements

1. The material is recycled, and/or biobased and/or derived from reuse
2. The material allows for form-freedom
3. The material is resistant to UV radiation, water and moist and wear and tear due to use
4. The material does not pollute the environment when it deteriorates
5. The production of the material requires low energy use and results in low carbon emissions
6. The processing of the material requires low energy use and results in low carbon emissions
7. The material can be recycled multiple times (in the Netherlands) without losing significant quality and requires low energy use and results in low carbon emissions
8. The material is sourced in the Netherlands (preferably from a waste stream) and can be processed into the final PE here
9. The material is lightweight
10. When applied in the PE, the material needs low maintenance, can be easily repaired and allows for a lifespan of at least 20 years
11. When applied in the PE, the material does not cause harm to its users

4.2 Reusing refurbished playground equipment

Reusing refurbished PE from depots offers commendable environmental benefits by reducing resource consumption. However, reusing PE from the depots has many limitations and challenges [45], as well as limit design flexibility. Furthermore, as it is the goal of this Master project to develop a product, and not just reuse existing ones, this approach will not be adopted in this project. However, as this is an interesting approach towards circularity, it will be discussed in Chapter 10 Recommendations.

Material choice contributing to the effective implementation of the circular product design principles in PE

4.3 Reusing 'waste' objects/ materials from other industries

Playgrounds can also be made from 'waste' objects, as some of these can fulfil the same play function as actual PE.

An example of this is the 'Blade made playground' or Wikado (Figure 22) from Superuse [119 (Appendix C.9)] which transforms discarded wind turbine blades into playground equipment. However, as was concluded by Medici [120], the playground has several issues that need to be solved before the concept can be replicated on a broader scale. These issues are related to the safety and appropriateness of materials. Therefore, a deep understanding of the reused objects and its materials is required in order to effectively apply it in playgrounds.

Reusing natural waste objects, like using old trees from felling work as a climbing device [121] (Figure 23) is an interesting approach. However, the quality of each individual tree will differ, and additional inspections are costly and not effective.

Construction waste objects, like old concrete tubes (Figure 24), could be retrieved from material marketplaces, like Insert, which provide more structure and knowledge into the reuse of these objects [124 (Appendix C.10)]. However, these marketplaces are still in an infant stage and need much more development to be effective [124, 125]. For example, the supply of materials is still low, and inspections are only performed once an interested party acquires the materials, as inspections are costly. Furthermore, municipalities, like Almere, do not want to join an outside company like Insert, as Rook [108] argues the following: "Almere is pursuing local circularity. As a result, participating in the national marketplace for circular construction, Insert, was not an option. Almere is a big city that is expanding with 860 playgrounds and 3,500 pieces of playground equipment. The city is big enough to be self-supporting by reusing playground equipment, parts and materials. As a result, we have no demand for second-hand stuff from other municipalities".

Because of the aforementioned reasons, reusing waste objects has not been adopted in this project.

Reusing 'waste' materials on the other hand could be an interesting approach. These could be retrieved from waste streams (of municipalities), such as waste wood, which can provide environmental benefits as the value of the 'waste' is retained [93], and no new virgin materials need to be supplied.

Figure 22: Blade made speeltuin [118]

Figure 23: Natuurlijk speeltuin Boskant [122]

Figure 24: Concrete crawling tunnel [123]

Material choice contributing to the effective implementation of the circular product design principles in PE

4.3.1 Reusing waste wood/ timber

Reusing waste wood/ timber would be an interesting approach as the significant amount of waste wood that disappears in the incinerator every year in the Netherlands is huge. Figures range from 2 million tonnes to even double this [126]. This concern was also expressed by C. van Eykelen [93].

To find solutions for this problem, Bluecity Rotterdam organized a hackaton in 2023, which, according to C. van Eykelen, was a needed development for the reuse of old wood as the municipality receives a lot of this material, without a plan on how to reuse or recycle it [93]. During this hackathon, structural solutions were presented to ensure that residual and scrap wood no longer ends up in the incinerator but gets a use in the Dutch wood economy [126]. As a result of this hackaton it was concluded that the environmental cost indicator of cross-layer wood from used material is 50% lower than that of cross-layer wood from new material [126]. Therefore, reusing this 'waste' wood in PE could be a valuable solution, also as wood is biobased and already widely used in PE, making it a fitting choice.

To conclude on the appropriateness of reusing 'waste' wood in C&S PE, more research was conducted based on the list of requirements as found in paragraph 4.1. To retrieve quantifiable material properties from Granta Edupack 2023, 'Hardwood: Oak, along grain' was chosen as C. van Eykelen stated that they receive a lot of waste hardwood furniture, such as tables and cabinets [93]. This makes sense, as hardwood is often used in furniture [127].

The analysis of 'waste wood' can be found in Appendix D.3.

4.4 Using recycled materials

Using recycled materials is a circular approach, as the value of the material is retained to some degree, depending on the quality of the material after recycling. Furthermore, by using recycled materials instead of virgin, less new materials need to be acquired, depending on the amount of recycled material used per product.

In order to make PE fit in the CE, it is important that it can be recycled at its end-of-life (after maybe several reuse cycles) (paragraph 3.8) and the recycled material can be used again with the highest possible value (so not downcycled). Therefore, materials have been selected which can be effectively recycled and used in new products, which will be discussed in paragraph 4.4.1 and 4.4.2.

4.4.1 Using recycled plastics

An interesting approach is to make use of recycled plastic, as (recycled) plastic is already used in PE, such as the Kompan products [128]. Furthermore, to even introduce plastic PE to municipal clients, it is needed to use recycled plastic, as they set high standards. For equipment made of more than 25% plastics, at least 50% of that total amount of plastics must be from recycled material. This could be post-consumer material (plastic waste thrown away by people or companies) but also pre-consumer material (cutting waste during production) [56].

To conclude on the appropriateness of using recycled plastic in C&S PE, more research was conducted based on the list of requirements as found in paragraph 4.1. To retrieve quantifiable material properties from Granta Edupack 2023 'Polypropylene (PP)' was chosen, as it is one of the most commonly used plastics [129]. Furthermore, Kompan, uses recycled PP for most of their recycled plastic PE [128], and therefore shows its effectiveness to be used in PE.

The analysis of 'recycled plastic' can be found in Appendix D.4.

Ocean 'recycled' plastic

Regarding using recycled plastic, a sidenote should be made on the use of 'ocean based/recycled plastics'. The plastic waste that enters the ocean can allegedly be retrieved and recycled into new plastic products, as Kompan [130] claims to have done with their 'panels made from 100% post-consumer ocean-recycled waste'. However, recycling ocean plastics is actually really difficult, as most of it, cannot be retrieved. Only approximately 3% of plastic in our oceans are thought to float on or near the surface and is highly contaminated and of poor quality [131]. As is concluded by Tombag [131], this 'ocean recycled plastic' is not actually plastic pulled directly from the water, but it is prevented from ending up in the oceans. Thus, it is actually 'ocean bound' plastic, which is plastic waste defined as 'at risk of ending up in the ocean' [132]. Therefore, it was my suspicion that Kompan also used ocean bound plastic, which was later confirmed by K. Dobbelsteen [133]: "Our GreenLine products including the panels are indeed sustainably produced. However, these are not made from recycled ocean plastic itself, but we prevent this waste from entering the ocean".

Therefore, 'ocean recycled' plastic PE does not exist to such an extent. For this reason, it should not be advertised as such as it could mislead unaware individuals. This is counterproductive, as it is important in the CE to correctly inform stakeholders to create a common, and correct, understanding.

4.4.2 Using recycled agricultural, industrial and demolition waste | Geopolymers

Concrete could be a very interesting material for the circular PE, as it is a big part of construction and demolition waste streams [134]. In the municipality of Leiden, it is by far the biggest [135] (Figure 25 & 26). This waste concrete is now low-grade recycled and mainly used in the foundation of roads [137 (Appendix C.11),138 (Appendix C.12)] and can only be used for 30% in concrete used for construction [137, 138,139]. As concrete production is responsible for 8% of annual CO_2 emissions worldwide, of which the main culprit is cement [140], it is important to effectively recycle this material and produce valuable new products in order to retain its value against its original environmental impact [141]. Recycling concrete will also enable considerable cuts in CO_2 emissions [142]. However, using recycled concrete aggregates also has several other environmental benefits [134]:

- Eliminate waste by recycling and reuse
- Help to solve some problems related to material scarcity
- Preserve natural resources that are not infinite, and depleting rapidly due to the vast development of construction industry
- Reducing the landfill areas
- Giving a second life to renewable and recyclable wastes
- Lowering the consumption of raw coarse aggregates, which then leads to reduction in costs, energy and pollution associated with the raw material extraction and transport

However, concrete is made by combining aggregates (sand, gravel or crushed stone), cement and water. During recycling, the aggregates can get separated from most of the cement and the other aggregates, which makes them useable in new concrete [143,144]. However, the recovered cement stone can only be used as filler (roughly 20% of the used cement) [145] and not as new cement which could serve as the binding agent (as it has already reacted with water). Therefore, when producing new concrete, all of the virgin aggregates can be replaced with recycled ones, but new virgin cement will need to be added in order to bind the aggregates and form a strong material [143]. Using recycled concrete therefore does not solve its main issue, which is its use of cement.

A solution exists to this problem: Geopolymer. Geopolymer is almost identical, if not better, to traditional concrete (TC) in terms of technical performance [146,147,148]. It is made from sand, gravel and stone derived from the recycling of concrete (recycled aggregate) and uses agricultural and industrial waste (geopolymers) as the primary binder [149,150] rather than using cement (which is the main cause of carbon emissions). Because of this, Geopolymer releases roughly 75-80% less carbon than TC [150,151,152]. It can even consist of only recycled aggregate [153,154,155 (Appendix C.13),156 (Appendix C.14),157 (Appendix C.15),158 (Appendix C.16),159 (Appendix C.17)], of which enough exists as it is one of the biggest waste streams in the Netherlands, and geopolymers, making it very environmentally beneficial, and can be recycled several times.

Because Geopolymer starts of as a soft paste, it can be poured into any shape by means of custom-made moulds or 3D-printing, which allows for creating many different shapes with both 2D and 3D possibilities. This makes it interesting for application in PE. Even so, applications in outdoor furniture and playgrounds already exist. Landscape Structures for example created the 'Facet concrete crawl tunnel' (Figure 27), while Playright created a playground which only consists of concrete tubes (Figure 28).

You can even make slides from concrete (Figure 29). The Lypa Concrete Slide for example, is a solid slab of reinforced concrete shaped, honed and polished to provide a smooth surface which can be used for sliding [163].

Furthermore, master students from the TUDelft developed 'The Concrete Turn' (Figure 30), which is reusable concrete outdoor furniture. These modules are made of Geopolymer, which is, according to van Gorkom et al. [165], a material that can be used for more than a hundred years, which allows CO_2 emissions to be reduced by up to 40 per cent. Furthermore, concrete waste can be used in the production of Geopolymer.

To conclude on the appropriateness of using Geopolymer with recycled aggregates in C&S PE, more research was conducted based on the list of requirements as found in paragraph 4.1. To retrieve some quantifiable material properties from Granta Edupack 2023 'Concrete' was chosen, as it shares many material properties with Geopolymer. However, several values, like carbon emissions of production, were not adopted as these differ from Geopolymer due to the different materials and chemical processes needed to produce this.

The analysis of 'Geopolymer with recycled aggregates' can be found in Appendix D.5.

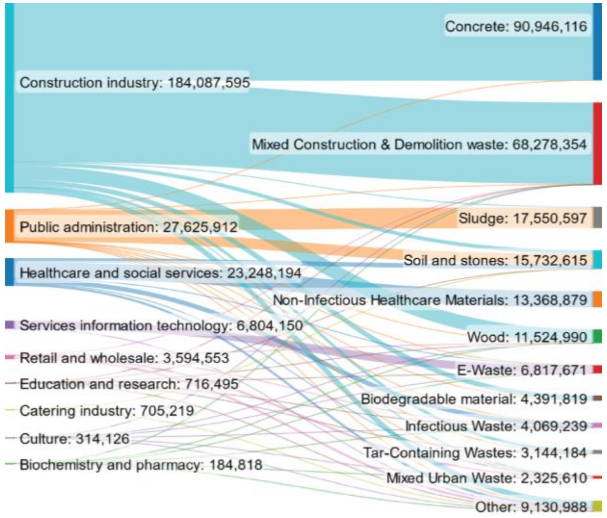


Figure 25: Sankey diagram of top 10 largest quantities of material Leiden material waste flows in kilograms, from contributing business sector to type of waste [135]

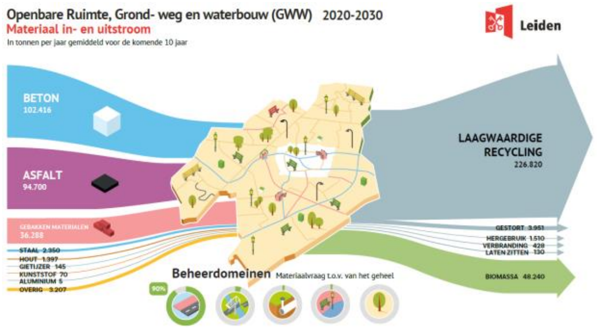


Figure 26: Roadmaps Circular Public Space in Leiden [136]

Figure 28: Concrete pipe playground [161]

Figure 30: Reusable concrete outdoor furniture [164]

Figure 27: Concrete playground equipment [160]

Figure 29: Concrete slide [162]

4.5 Using renewable biobased materials

Renewable biobased materials are an interesting approach to developing sustainable PE, as they create environmental benefits as opposed to using conventional building materials.

Firstly, biobased materials have an advantage over conventional building materials because they can store CO2 for a long time, since they are obtained from plants which capture CO2 from the air during their growth [166]. This is also the case for waste wood, which is discussed in paragraph 4.3.1. Secondly, by using bio-based materials, wastages, landfills and toxic emissions are reduced [167]. Lastly, as the name suggest, renewable materials are regenerative, therefore it is an inexhaustible resource.

In order to make PE fit in the CE, it is important that the developed PE can be recycled at their end-of-life (after maybe several reuse cycles) and the recycled material can be used again with the highest possible value (so not downcycled). Therefore, materials were selected that can be recycled to some degree.

4.5.1 Biobased waste material

An interesting approach to using biobased waste material is by creating panels from it. Ecor has done this, and created a bio-based, additive free, fibre board made from 'cellulose waste fibres' such as 'cow dung, waste grass (from for example Schiphol) or hemp dust'. This would be a sustainable solution as it is made from locally sourced waste, production requires low energy and results in low CO2 emissions (and can be performed locally) and is suitable for high-quality recycling due to its lack of additives or binders (and can be recycled 25 times without losing quality [168 (Appendix C.18)]. However, because the panels just consist of cellulose waste fibres, rain and moist will cause quick deterioration. Therefore, using only biobased materials is not suitable for products with an outdoor application, such as PE, and was therefore not investigated further.

4.5.2 Drop-in bioplastics

Drop-in bioplastics are almost identical to petrochemical plastics. The main difference is that bioplastics are made from biomass instead of fossil-oil. Examples of drop-in bioplastics include bio-Ethylene, bio-polyethylene (bio-PE), bio-propylene (bio-PP) and bio-polyethylene terephthalate (bio-PET) [169].

Using drop-in bioplastics, as opposed to fossil-based plastics, has an advantage as it is made from a renewable resource. Furthermore, factories can replace fossil-based plastics by drop-in bioplastics while using the same machinery and equipment. Therefore, it does not require additional changes or factories to produce drop-in bioplastic PE [169].

To conclude on the appropriateness of bioplastics, Bio-PE was chosen as this is one of the most used bio-polymers in the world [170]. Mechanical properties of bioplastics could not be retrieved from Granta Edupack 2023, and were therefore mainly left out, besides what could be retrieved from academic sources. As a convenience, bio-PE was examined and compared directly with recycled fossil-based plastic (Appendix D.2), as their chemical, physical and mechanical properties are identical [170]. Also, this way it was immediately visible which material would be more environmentally beneficial.

The following conclusions were drawn based on the comparison found in Appendix D.2:

- Recycled plastic and bioplastic are similar in their material properties, production, processing and recycling possibilities. Furthermore, they both cause microplastics [171].
- When material production and processing of bio-PE and petroleum based PE are compared, bio-PE results in lower carbon emissions. Furthermore, when the energy use and carbon emissions of recycling of PP and producing of bio-PE (as these are both the birth step of plastic granulate to produce the playground equipment) are compared, energy use is 250% lower and carbon emissions 200% lower of bio-PE when compared to PP [171,172,173]. However, as bio-PE will probably be produced outside the Netherlands, transport should also be included in this comparison, which increases the energy use and carbon emission of bio-PE, thus decreasing the difference between recycled plastic and Bio-PE.
- Plastic waste can be retrieved, recycled and processed in the Netherlands, while the biomass of bioplastic (sugarcane or corn) will probably needs to be grown and processed outside the Netherlands. This results in additional significant amounts of land and water use, which would increase competition for different land uses and have a negative effect on biodiversity [174].
- A benefit of recycled plastic is that it retains the value of the originally produced plastic, while bioplastic needs to be made new [175].
- A benefit of bioplastics compared to recycled plastics is that it captures carbon dioxide, therefore neutralising its carbon emissions [171].
- Bioplastics can cause mayor health problems [174].

Using recycled plastic instead of bioplastics results in less environmental impact, mainly because it retains some of the value of the original virgin plastic and can be retrieved and processed in the Netherlands, as opposed to bioplastics. This reduces the difference in energy use and carbon emission and requires additional land use which causes a negative environmental impact. The production of bioplastics also causes health problems. Therefore, using recycled plastics is preferred.

4.5.3 PLA

Research was conducted on the use of PLA for a potential panel application, as Biopanel uses PLA in their outdoor road sign panels. However, in order to be applicable in outdoor conditions, the PLA needs additives, which makes it brittle and is therefore not suited for children to play on, as it can break more easily [176 (Appendix C.19)]. Furthermore, PLA products lose their strength fast. After 10 years, the Biopanels only have 30% of their original strength, which is mainly due to UV radiation [176]. This makes it not suitable for outdoor PE and was therefore not investigated further.

4.6 Conclusion on material choice

Using waste wood, recycled plastic or Geopolymer (with recycled aggregate) are the most promising material applications and were therefore compared (Appendix D.6). From this comparison it can be concluded that using Geopolymer as the base material of PE is most beneficial regarding C&S.

Geopolymer with recycled aggregates is made from recycled and reused waste materials. Even so, concrete is one of the most abundant resources in the world [177], and a big part of Dutch waste streams [135], making its use a valuable addition towards the CE. Geopolymer products can even be made with 100% recycled aggregates and geopolymers [143,153,154,155,157,158,159]. Therefore, in theory, no virgin materials are needed. Also, the reuse of the agricultural and industrial waste prevents them from polluting soil and water [178], creating further environmental benefits. The use of recycled aggregates and geopolymers also significantly reduces the carbon emissions of production when compared to traditional concrete (TC) [143,150,151,152,179].

Geopolymer can be moulded into many shapes and sizes [138,157,180,181 (Appendix C.20),182 (Appendix C.21),183], making it appropriate for mono-material design, which benefits both material use and the demolition and recycling process. Furthermore, Geopolymer structures are very durable. It is highly resistant to wear and tear [144 (Appendix C.22),147,148,155,182], UV radiation [185] and water and moist [186], as opposed to for example reused wood.

It can have a lifespan of 50+ years [138,187] with easy repairs and minimal maintenance [138,188] which is valuable for a modular system. Even so, Geopolymer improves the service life of structures as compared to TC [150].

Geopolymer can be produced in the Netherlands [158,159,182,183,189] with resources obtained in the Netherlands (and surrounding countries) [155,157,158,159] and can also be recycled here, without the need for new methods or plants [145,157,158,159,181,182,190,191]. This has a positive effect on the transport of materials and products. The Geopolymer PE can be efficiently recycled at its end-of-life, and the recycled aggregates can be used again in new 'concrete' products. Combining Geopolymer and TC during the recycling process will not cause problems, and the aggregates can be recycled and reused several times [143,144,181].

Geopolymer can even be coloured (Figure 31), which will not become a problem during or after recycling, as the small amount of coloured aggregate will fade away amongst the greyish aggregate [138,157,159,181,182]. This application will make the playground more 'child-friendly looking'.

Figure 31: Urban Concrete Playground Elements [192]

Geopolymer can be considered heavy which increases CO2 emissions due to transport. Using recycled aggregates already reduces the weight of Geopolymer structures [193]. To minimize weight, shapes should be optimized to decrease the amount of material. A benefit of this weight is that it can be considered 'hufterproof'.

As concrete is the most man-made used material in the world, many companies and organisations are looking for solutions to reduce the CO2 emissions of concrete production. Geopolymer is one of these solutions, but many more developments are being made, like producing concrete without cement, capturing CO2 during the production or producing concrete without CO2 emissions [194]. As Geopolymer and concrete share part of the same materials, the aggregate, it is possible to change the 'recipe' of the Geopolymer PE when new material developments arise, and therefore shows great promise and possibilities for the future. As aggregate recycling is quite efficient, several materials of the old Geopolymer PE can be recycled into new products or even new PE.

When asked about developing PE, made of coloured Geopolymer with 100% recycled aggregate, with all raw materials coming from the Netherlands, and the recycling and production of the PE also taking place in the Netherlands, P. Wolterink (Hoofd kwaliteit beton Rouwmaat) [159], G. van den Bosch (CEO Bosch Beton) [195 (Appendix C.23)] and M. de Graaf (Rutte Groep) [196 (Appendix C.24)] confirmed this is possible.

4.7 Comparing 3D-printing vs casting of Geopolymer

During a visit to the Dutch Design Week in Eindhoven (Figure 32), I got inspired to see if it was possible to 3D-print Geopolymer as opposed to casting (Figure 33). Dutch companies like Witteveen+Bos [198] and Saint-Gobain Weber [199] have already worked with Geopolymer 3D printing and have created structures like bicycle bridges [200,201,202], houses [203], stairs [204], benches [205] and skate-park elements [206]. Buřinka (Czech Republic) even created a 3D printed parkour playground (Figure 34) [208].

When compared to both casting and 3D printing of TC, 3D-printing of Geopolymer has several environmental and economic benefits [209,210,211,212]. For example, printing Geopolymer results in a lower waste generation in the manufacturing processes and no mould is needed [210,212,213]. The created structures have shown better environmental performance in global warming potential and fossil fuel deposition [212,214].

Figure 33: Concrete block-moulds [197]

Figure 32: 3D-printed concrete bench at the DDW

Figure 34: 3D-printend parkour playground [207]

Therefore, I have compared both the 3D-printing and casting of Geopolymer, based on a secondary data analysis, and formed on conclusion based on their environmental benefits or impact and their potential effective application in circular modular PE.

When comparing the mechanical properties of casted or 3D-printed Geopolymer structures, Korniejenko et al. [215] and Munir & Kärki [210] conclude that the mechanical properties of the 3D-printed structure is comparable with the results achieved by the traditional casting process.

However, 3D-printing of Geopolymer has several benefits when compared to casting. Firstly, it allows for more freedom of form [216], allowing to create more intricate structures. Unnecessary material use is decreased, as concrete material will only be added to the areas where it is needed constructively [216]. Because no mould is needed, significant costs can be saved (such as material and labor costs) as well as reduce environmental impacts [211]. Al-Noaimat et al. [217] even concluded that because formwork labor is not needed, the production cost can be reduced with 50%. Munir & Kärki [210] conclude that 3D printing of Geopolymer reduced the construction time and decreased the energy demand by nearly 50%. Secondly, 3D-printing, as opposed to casting, allows for a reduced lead-time [210,211]. However, when producing many of the same prefab elements this might not be the case.

In contrast, Liu et al. [218] argue that the environmental performance of 3D printing does not exceed casting, which is due to the additional activators, additives and superplasticizers (alkali activators) needed to make the geopolymers workable and printable for massive prints [219]. However, after a conversation with an actual 3D Geopolymer printing company (Renca), they pointed out to me that several theoretical entities, which are not connected to actual construction and manufacturing, often misuse the terms Alkali-Activated Materials (AAM) and Geopolymers and they actually describe and study different materials [220]. Davidovids [221] confirms this, stating that they belong to two very different and separate chemistry systems, where people claiming that both terms are synonyms are promoting a misleading scientific belief. Reggiani [220] also pointed out that the LCA's should be critically assessed, as equally printing and casting of the same structure could theoretically result in these outcomes but is far from true in real applications as printing has many environmental benefits as compared to casting. This is true, as Liu et al.'s [218] conclusions are based on the equal production of a 1 cubic meter Geopolymer product, without taking into account any other environmental benefits.

Reggiani [220] concludes that the amount of alkali doesn't change over casting or 3D printing. What changes is the amount of concrete needed for 3D printing which is three times lower, so the alkali content lowers too.

The environmental benefits of 3D printing over casting was also confirmed by P. Cornelissen (Saint-Gobain Weber) [222], as he states that geopolymer mortar used for 3D printing can have many different compositions of materials. Therefore, it really depends on this composition if there are actually more additives incorporated in the mixture. In their case, they produced a mixture which significantly reduces the CO2 footprint. This is also because there is a significant reduction in the amount of used concrete. P. Cornelissen further stated that "if you compare printing and casting, printing is more environmentally friendly". They compared the production of a 'taludtrap' (stairs) with both printing and casting and concluded that there is a 60-70% reduction in CO2 footprint. Furthermore, the energy consumption of printing is quite low and comparable to casting. Another big difference is that with casting you have to produce a mould, and the automatic casting also consumes energy. Furthermore, casting often needs steel reinforcements, which also need to be produced and complicates the recycling process. M. Bruurs (WitteveenBos) [223] further confirmed the conclusions of Cornelissen, stating that design optimisations can be made relatively easy with printing, which means you need significantly less material. However, this is application-dependent and to make substantiated claims an MKI calculation of different design variants should be conducted. In the case of a Geopolymer stairs that they produced, this has been done and the MKI was 50% lower for printing when compared to the poured version.

Therefore, it can be concluded that 3D-printing of Geopolymer is a more preferred option, when compared to casting, when considering the sustainability. Nonetheless, a definitive conclusion can only be based on an actual MKI calculation and should be performed. However, as this is beyond the scope of the project, as described in this thesis, such an MKI has not been performed. However, as this is of value it will be discussed in Chapter 10 Recommendations.

4.7.1 Visit concrete and Geopolymer 3D-printing facility

On the 7th of December I visited Weber in Eindhoven (Figure 35) to get a better insight into 3D Geopolymer printing, get inspired and really get in contact with the material (look & feel, weight, etc.) and discuss several ideas with P. Cornelissen (Business Unit Manager 3D Printing – International 3D project Manager).

Material look & feel

When touching the material, it feels quite soft and smooth, which was something I did not expect. The chairs are comfortable to sit in too (Figure 36), as their shape forms nicely around a human body and the material feels soft. This has a positive effect on the playability and comfort.

Colour can be added in the printable mortar. For now, Weber only produces grey and anthracite products (Figure 36) but other colours are possible [216]. Furthermore, a wrap can also be added to the printed product which could have any illustration on it (Figure 37). Additional coatings can be added to make the wraps resistant to wear and tear. Furthermore, these wraps will not cause problems during recycling, as it is a very thin film. This opens up possibilities to add markings, logo's, illustrations or game elements (for example a checkerboard).

If needed, the surface can be sanded to create a smooth surface. This was applied to the 'Perfect Wave' skatepark element (Figure 38). However, the rough surface of the printed layers actually looks more natural, almost like a mountain or rocks. However, as expressed, it does not feel rough or sharp. A sanded surface, as also expressed in paragraph 4.4.2, could be used as a slide.

Shape possibilities

Many shapes can be created (Figures 39 to 40). To create protrusions and recessions in the X and Z direction is simple (Figure 41), as the path of the print line determines these shapes. For example, when the stairs in Figure 41 is tilted, the protruding steps are created. However, to create protrusions and recessions in the Y direction of printing is more difficult as overhangs are harder to create as the mortar is still soft (fresh state of the material) when it is printed and won't harden quick enough [216]. Optimizing several printing parameters can enable printing supports with the primary material to create an overhang (Figure 42 (left)) [225]. However, this results in additional manual labour to remove the support, as well as create waste. The resulting opening (Figure 42 (right)) also looks messy. Overhangs can also be created by adding an additional overhang (Figure 43) [225] which would be the preferred method.

Figure 35: 3D-printers at Weber

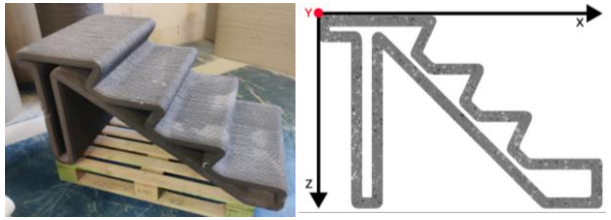


Figure 41: Printed stair element (left) and illustration of directions of printing (right)

Figure 42: Printed supports (left) and resulting structure (right) [224]

Figure 43: Additional overhang [226]

4. Theoretical framework

Material choice contributing to the effective implementation of the circular product design principles in PE

Figure 38: The Perfect Wave smooth outside (left) and internal structure (right)

Figure 37: Checkered print wrap on 3D-print

Figure 36: Anthracite printed chair

Figure 39: Printed bicycle, Christmas tree and cabinet

Figure 40: Printed hexagon structure, picknick table with seats and star

Textures
Several textures can be created to add more depth, create patterns or add a logo (Figure 44 and 45). Again, due to the behaviour of the material there is a limit to how far these textures can protrude. These textures can be utilized in the PE to create climbing elements or a more natural look & feel (rock texture). Furthermore, the advantage of 3D printing is that these textures can be easily added in the print file and does not change anything in the production process. This is different for casting, as new moulds are needed for each new texture or logo.

Weight
Upon lifting several printed objects, it was concluded that lifting them by hand is not possible by one person. This allows the PE modules to be placed and stacked without having to secure them to the ground, as there is no way the modules could be taken or moved by people. Furthermore, it is possible to print different thicknesses (Figure 46 and 47), which allows to find a balance between strength and weight.

Strength
As the material is very rigid it can withstand a lot of weight without collapsing. Because of this some structures do not need much internal support (Figure 36). However, if the size of the structure, or the amount of weight it needs to carry, increases additional supports should be added.

Connections
The modules can be easily connected by nuts and bolts (Figure 48), and additional elements like poles can also be connected this way. As the printed structures always have an open side, reaching these connections becomes much easier which allows for speedy maintenance, repairs or removal. Furthermore, connecting the Geopolymer modules together by means of slots or jigsaw shaped connectors (mono-material connections) should also be possible if the design allows for this [216].

Damage and repairs
When the layers of the materials are stacked on top of each other during printing, they are morphed together, creating a solid structure. Therefore, should a piece break of, it does not necessarily break between two printed lines (Figure 49). Holes or broken-off parts can be easily repaired by adding new material, sometimes with the need of a form box [216]. This form box can be made from wood, filled with the original material and when the material hardens it looks like no damage was done (Figure 50).

Figure 48: Steel handrail connected to 3D-printed structure with bolts

Figure 49: Damaged 3D-printed structure at Weber

Figure 50: Repair with wooden form box [227]

Figure 44: 3D-printed textures

Figure 45: 3D-printed logo of Weber

Figure 46: Thin printed seat

Figure 47: Thin printed vase

4.8 Comparing bamboo vs steel poles

Poles can add a lot of play functions to a playground, like tumbling, climbing, swinging and sliding (Figure 51). They can also create dimensions to a playground, as they can form roofs, walls and fences. Steel is often used in playgrounds to fulfil the just mentioned play functions. As steel is durable it has quite a long lifespan (40-70 years) [97]. Because of this, playground equipment depots have a lot of stainless steel [45]. Its long life would also make it suitable for reuse, as is sometimes already done [97].

Besides steel, bamboo could be an interesting choice as the material for beams and poles, as it has comparative material properties in terms of strength compared to steel [229,230,231]. This makes it suitable for structural applications [232]. Furthermore, Its natural aesthetics could elevate the Geopolymers 'industrial' look and feel. Several bamboo playgrounds have already been developed (Figure 51, 52 & 53).

Reusing steel beams and retrieving them from, for example, playground depots would also be an interesting approach to a more circular playground. However, as steel beams and poles have different widths, sizes and qualities, it will be difficult and time consuming to find the right equipment which will fit the concrete playground elements [97]. Therefore, this was not investigated further.

As was discussed in paragraph 3.3.1, an effective way to reduce material diversity in a product is to make the product from a mono-material in which all the functionalities can be integrated. This also creates benefits for recycling, as is discussed in paragraph 3.8, as mono-material products can be efficiently recycled without the need for additional dis-assembly steps. Therefore, in theory, producing the beams and poles from Geopolymer would be beneficial in a circular point of view.

However, creating beams and poles from this material is not very realistic. The width of a print line is minimally 30 mm, which would create a pole with unnecessarily thick walls which makes it very heavy. Printing circles in the y-direction of printing to create such a pole is also not doable. Due to the height and the softness of the printed material this pole will most likely collapse during printing, which was also the case in a test print from Weber, which can be seen in Figure 35 on page 27.

It would be possible to cast this Geopolymer pole, but multiple moulds would need to be created to produce different lengths of poles. Furthermore, such poles will become very heavy, and due to the relatively small radius will need steel armament which is not beneficial for the recycling process. Because of these reasons, Geopolymer was not selected as the material for the beams and poles.

Bamboo and recycled stainless steel (as this is often used in playground equipment [63]) have been compared (Appendix D.7) based on the list of requirements as found in paragraph 4.1. Again, quantifiable material properties are retrieved from Granta Edupack 2023. Other relevant information is derived from secondary data analysis.

The following can be concluded based on the comparison:
- Both bamboo and stainless steel are durable and have a comparative tensile strength [230,231,232]. However, bamboo has a much lower weight, which makes it more efficient to transport.
- While steel needs several high-energy and carbon emission procedures to be formed into a tube, bamboo is already grown this way. Therefore, the manufacturing of bamboo is much more environmentally friendly then steel. Also, bamboo can sequester CO_2, reducing the carbon footprint even further [235,236].
- Bamboo cannot be recycled, as compared to steel which can be recycled many times [237,238,239,240]. However, as the production of steel products results in significant carbon emissions and energy use [231,235,236] the recyclability of steel is not necessarily an environmental advantage.
- Bamboo can be sourced in the Netherlands [241], eliminating the need for transportation from countries outside of Europe which would increase the CO_2 footprint.

Because of these conclusions, bamboo was chosen as the material which will be used in the PE.

Furthermore, combining Geopolymer and bamboo can create an interesting dynamic in several ways:
- They touch upon different aspects of circularity. While the Geopolymer equipment will have a lifespan of 50+ years and needs limited repairs, the bamboo parts have a much shorter lifetime, cannot be repaired so easily and will therefore need to be replaced multiple times throughout the lifetime of the PE. Therefore, the bamboo will be used for parts which will endure a lot of wear and tear due to tumbling, swinging, walking over, etc.
- Geopolymer is made from waste (recycled materials) while the bamboo is bio-based. This creates PE which touches upon multiple facets of sustainable design.
- While the Geopolymer is fabricated with exact measurements, the bamboo is grown and organic. Therefore, the bamboo will give the playground a more natural look and feel to the otherwise 'industrial' looking Geopolymer.

4. Theoretical framework

Material choice contributing to the effective implementation of the circular product design principles in PE

Playability and safety of bamboo in playgrounds

Bamboo has already been used in several playgrounds around the world, such as Thailand (Figure 51 & 52) and Belgium (Figure 53), showing its applicability in such a use case. However, even though this is the case, its use in Dutch playgrounds is still limited. Therefore, concerns were raised by van Ee [242] regarding the playability and safety of bamboo. Van Ee Speel has already worked with this material in a past project and the following concerns were mentioned:
1. The bearing strength might not be enough
2. Drilling holes can cause splits
3. Extensive handling of the bamboo poles, such as climbing and swinging, could cause splinters

Therefore, I conducted research on the use of bamboo in playgrounds to conclude on the significance of these concerns, and if solutions could be found.

Firstly, as was already discussed bamboo has a comparative strength to steel, which is a widely used material in playgrounds for climbing and swinging applications. Therefore, in terms of strength bamboo is more than suitable for use in PE.

Secondly, when drilling holes in bamboo, splits could always be caused. However, this is no different from wood. The main point of attention here is to use the correct tools and handle the bamboo with care, which will significantly decrease the change of splits due to drilling [243].

Lastly, getting splinters from handling bamboo is almost zero which is due to its natural smooth surface. As was expressed by an employee from Bamboo Import: "I have been handling bamboo for years, and I have never gotten a splinter" [244]. Splinters are more prone to happen with using wood, which is a very popular building material in playgrounds. Therefore, this should be of no concern.

However, to be a hundred percent sure of this a coating could be added to the bamboo poles, which will also extend the life of the already durable bamboo. This coating can protect the bamboo against UV rays, water, weather and other exterior exposures such as wear and tear due to use [243]. This protective coating can be made from purely bio-based materials [245,246], and therefore does not negatively influence the bio-based aspect of using bamboo or cause harm to the surrounding vegetation.

To conclude, bamboo is a suitable material to use in PE as it is strong, durable, lightweight, workable and causes no harm to playing children.

Figure 51: Bamboo monkey bars [228]

Figure 52: Bamboo playground equipment [233]

Figure 53: Bamboo playground Antwerp [234]

5.1 Playgrounds in the municipality

As I found throughout my research, as presented in this thesis, municipalities have a substantial influence on the implementation of C&S PE, as they formulate the regulations and are often the ones paying for them. However, even though they argue that they are working towards circularity (paragraph 1.2), for example with the Leidse ladder, there are still several issues which are caused by municipal decision making. Oost-Mulder & Van Weert [4] concluded on a few of these issues, which will be discussed and related to interviews with employees from the municipality of Leiden.

Circular requirements are requested but not checked afterwards

Municipalities often request contractors to abide by their circular and sustainable requirements, such as the LL. However, Oost-Mulder & Van Weert [4] argue that as the requirements are not checked, companies promise all kinds of things, but, due to cost considerations or participation motivation, do not fulfil them. When asked about this, E. Bosch (policy officer for circular construction in the municipality of Leiden) [9] mentioned that the municipality of Leiden does thoroughly check the proposals that they receive, also by making use of the LL. This was confirmed by van Ee. Therefore, it would seem that the municipality of Leiden is progressive when compared to other municipalities in the Netherlands regarding circularity, as was also stated by E. Bosch [9]: "The municipality of Leiden is seen as a leader in the field of circularity and specifically for circular construction. […] Therefore, we are organizing a day in November in which we involve as many municipalities and other (semi) government bodies as possible in the creation and operation of the LL. We hope to achieve that other organizations can more easily guarantee circularity in their public space projects".

Insufficient budgets cause 'boring' playgrounds

It is estimated that in over 50% of municipalities the available replacement budgets are not sufficient to maintain the current inventory. Even so, between 35% and 55% of this amount is spent on shock-absorbing surfaces [4]. As a result, the remaining but lean budget can only be spent on cheaper and more 'boring' equipment than desired.

PE prices are unrealistic due to price-driven tendering

As was concluded by Oost Mulder & Van Weert [4], price weighs more than 40% in calls for tenders. Particularly, calling out discount rates on list price and calling out mini competitions without design fee. Both ensure that standard list prices are roughly 20% higher than the 'clean' prices. During the municipal meeting on the 15th of August these 'mini competitions' were discussed, with the conclusion from most of the participants that they should be included in projects as they result in playground developers offering more interesting ideas. However, as can be concluded it can also work counterproductive.

Municipalities have almost no playground equipment that is the same

Because no two pieces of PE are the same, modularity and interchangeability are made difficult within municipalities [4]. A seesaw may come in 1,200 variants (Figure 54), but the playing function or play value is exactly the same. For children, it doesn't matter what type of swing they sit on: as long as it goes high, or they can sit on it with more children at once. This again highlights the importance for designing for play function rather than focus on specific equipment.

As can be concluded from this, effective implementation of the design principles to the development of sustainable PE is partly dependant on the behaviour of municipalities. However, due to the purpose of the project as described in this thesis, a proposal to Dutch municipalities will be discussed in Chapter 10 Recommendations.

Figure 54: Selection of seesaws in the municipalitiy of Amsterdam [247]

To gain inside knowledge into the method of operations and considerations of a municipality regarding playgrounds, a meeting on the 15th of August was attended in which members of the municipality of Leiden discussed their contract for the playground developers for the coming years. Here, they also discussed their concerns and ideas. During this meeting, several interesting conclusions came forward (Figure 55). The conclusions of this session were complemented with the conclusions from conducted interviews to uncover a consensus between the two.

A better understanding of 'safety' in PE is needed to create more challenging playgrounds

Due to the strict safety regulations, playgrounds can sometimes be 'boring'. To change this, municipalities, parents and schools should be informed on this matter and together with these stakeholders a new way of looking at safety should be developed. This can partly be realised by involving parents and other volunteers in the maintenance procedures [40,248,249,250]. When this change in perception, and maybe even the regulations themselves, have been made, more adventurous and challenging playgrounds can be designed which encourages children to play outside more [4,5,40,246].

More inclusive playgrounds should be developed

Inclusivity in playgrounds (Figure 56) is an upcoming development to ensure every child can play outside, as there are about 100,000 children with disabilities in the Netherlands. 10 years ago, there were only 2 special playgrounds for them. Luckily, now there are 113 [252]. When relating this to sustainability, inclusivity mainly relates to social benefits as it enables a wider group of children to enjoy the playground, thus improving the overall wellbeing of children.

Inclusivity was also discussed in the meeting, and it was concluded that more playgrounds should be developed with this in mind [248,249].

This has already been done by several playground developing companies. Kompan developed '6 points of attention when designing inclusive playgrounds' [253] and Ijslanders developed a whitepaper 'How to make inclusive playgrounds' [254]. Furthermore, conclusions from studies by Brown et al. [255] 'A scoping Review of Evidence-Informed Recommendations for Designing Inclusive Playgrounds' and Mor [256] 'Inclusive Playground Design: Promoting Social Inclusion for Children with Disabilities' can be used to design inclusive playgrounds.

However, what is important to note is that inclusive play does not always require expensive adjusted play equipment. Much more emphasis should be placed on offering opportunities for children to play together without shame or barriers.

To realise this, communication between families, schools, playground associations and non-profit organisation like the 'Speeltuinbende' is needed [257].

The municipality of Leiden already works together with the 'Speeltuinbende' [42,249] which is an initiative from the foundation 'Stichting het gehandicapte kind' where a group of children with and without a mental or physical handicap test playgrounds on its inclusivity [258].

Modular playground equipment

An interest for detachable and moving (modular) playground equipment was also expressed, as this can offer a lot of variety both in play functions and exercise possibilities (exercise all muscle groups) [39,42,44,248,249].

Figure 55: Idea board playground meeting municipality of Leiden (August 15 2023)

Figure 56: Inclusive playground equipment [251]

5.2 Parallels between desired play functions and an increase in physical activity and wellbeing among children

To conclude on design considerations which increase both outdoor play, physical activity and child wellbeing, it is important to find a potential parallel between the three. I have conducted research on this topic, and formulated a conclusion based on the secondary data snalysis of academic research.

As was concluded by Graham et al. [259], playground designers should consider several defining characteristics of playground areas to enhance physical activity levels among children, especially MVPA (Moderate to Vigorous intensity Physical Activity). Play areas that encourage climbing, team sports, and adventure play have shown to promote the highest levels of MVPA during break times. This is in line with conclusions from Raney et al. [260], who argue that climbing and jumping could contribute to motor skill development in the areas of balance, coordination and agility. They furthermore conclude that imaginative play can increase development skills, such as communication, negotiation, cooperation, sharing, problem solving, and coping. In a study by Reimers et al. [261] it was determined that 'things to climb up' was the equipment that was used the most by children, with Adams et al. [262] adding to this, concluding in their study that the second most observed FMS (Fundamental Motor Skills) is climbing, with climbing nets being the most used piece of equipment, where parents argued that climbing features encouraged their child to be active. Climbing nets are important, as children can practice their climbing and hanging skills and develop upper-body strength [262]. Furthermore, swings and slides are also popular equipment, with parents stating that swings, slides and climbing facilities encouraged their child's physical activity [262], which was later also established by Veitch et al. [263].

These conclusions are in line with the view of playground equipment developing companies on increasing the physical wellbeing of children. 'Playground Equipment' and 'Little Tikes' encourage climbing, as it helps children with building lower body function and muscle strength, sliding, as it increases flexibility and maintaining balance, and swinging, as it provides a means of helping children learn how to better focus on their balance, synchronized movements and coordination [264, 265]. 'PlayPower Canada' concludes that equipment like swing sets, monkey bars (climbing), slides and sports equipment can be great for kids to work out and develop an enjoyment for exercise [266].

When looking at the potential 'risk' of playing, especially climbing, Sando et al. [267] actually found that 'risky play' is associated with positive outcomes in children, including increased well-being, greater involvement, and more physical activity during free play, potentially reducing long-term injuries.

Furthermore, despite growing concerns about risk, around 12% of observed playtime was categorized as risky play, indicating its popularity. The benefit of risky play and climbing is further backed up by Gull et al. [268], as they conclude that "children that afforded the opportunity to be involved in risky play such as tree climbing have the potential to grow socially, emotionally, physically, cognitively, and creatively, and have increased resiliency. Bans on tree climbing and other risky play pose problems such as limiting access to natural spaces, creating fear of participation in adventurous activities, and fewer opportunities to negotiate risk and develop resiliency".

Additionally, Stanton-Chapman et al. [269] conclude that if the goal of playgrounds is to encourage physical activity and social interaction among children, fixed play equipment and open play spaces are critical elements in overall playground design, where future playground designs should incorporate unique and challenging equipment concepts. Cetken-Aktas & Sevimli-Çelik [2] further conclude on 'fixed play equipment', where if it included a themed play structure such as a castle or ship, the children's play became more dramatic and social. However, they advise that designers should be cautious when including such prescribed manufactured equipment where the theme might dictate the play type of children.

To compare the academic research with real life data, a context mapping- and design session with school children aged 6-11 was performed. The results of which can be found in paragraph 6.2..

5.3 Playground safety

To create a save playground it should be conform the 'Warenwetbesluit Attractie- en Speeltoestellen' and the NEN-EN 1176-1 – 6 and NEN-EN 1177 for fall heights, among others [94]. However, even though playgrounds should be designed for safety to minimize injuries, a balance should be found between rules/ safety and freedom, risk-taking and creativity to keep the playground exciting [4,5,39,40]. This is in line with conclusions from Sando et al. [267] and Gull et al. [268], who highlight the need for more adventurous playgrounds which facilitate risky play as these create several physical and emotional benefits.

5.3.1 Climate-smart playgrounds

As a result of climate change the temperature on earth will increase [270], which results in playground surfaces absorbing heat, which can burn playing children, and an increased risk to develop skin cancer due to UV radiation [271]. To combat this, PE should be designed with a 'climate-smart' approach [39,119,272]. This allows children to play outside longer, which in turn will improve their physical health and support cognitive development [272].

6.1 Effective implementation of the circular principles

Product designers/ developers can increase the circularity of PE by considering how to effectively implement each of the 10R design strategies in the design. When design considerations have been implemented, such as a durable material, which allows the PE to last for decades, it can be effectively used in the CE. Design considerations can also increase the sustainability of the PE by making decisions throughout the design to lower the environmental impact of the PE in all aspects of its life, like production, material, maintenance, recycling, etc.

The circular design principles have already been implemented in playgrounds and PE design in several ways, many of which have been discussed in Chapter 3. In the following paragraphs, I want to further elaborate on effective implementation of these principles, by means of design considerations, thus answering sub-question 1. I implemented several of these considerations in the final PE design as described in this thesis, which can be found in Chapter 7.

6.1.1 Effective implementation of refuse, rethink & reduce

Overall, refuse, rethink and reduce (R3A) have been effectively implemented in PE in a variety of ways, as the solutions offer the same functionality and playability while decreasing the number of parts and materials. The overarching theme here is 'designing with smart solutions' which can be subdivided in the following approaches: Make use of what is already on site, combining functions of a single element, eliminating redundant elements, incorporating nature and natural processes and encourage and facilitate imagination.

However, to further implement reduce more effectively in the PE, a mono-material approach should be considered. By creating playground equipment which is (for the most part) made from a mono-material and combining this with approaches such as 'combining functions' and 'eliminating redundant elements' PE can be created which needs significantly less material.

Even though 'make use of what is already on site' and 'incorporating nature and natural processes' are effective methods, they are not implemented in the proposed PE, as described in this thesis. The reason being that the objective of this project is to design new PE, and not just reusing what is already there.

6.1.2 Effective implementation of durability

Durability in PE design has mainly been implemented by means of choosing durable materials, such as wood and steel, which can endure changing conditions over time. These conditions could be wear and tear due to use and external forces such as weather conditions.

In turn, durable material choice allows the PE to have a long life, without the need for extensive maintenance, repairs or replacements [60]. Thus the PE's total environmental impact is reduced across its lifecycle [62]. However, to implement durability more effectively, the following must be considered.

Consider the behaviour of the chosen material and make design decisions accordingly. For example, wood can expand and shrink due to weather conditions, which can weaken connection joints. By designing joints which can adapt according to the expansion or shrinkage of the wood, less damage occurs.

Besides considering the durability of the material, also consider the material of the surroundings of the PE. For example, wood is considered to be a durable material. However, when placing it on a sandy substrate, the sand causes abrasions which increases wear and tear of the equipment. This in turn could result in more repairs or even replacement. However, even though this method can increase the lifetime of the PE, it was not included in the design as proposed in this thesis, as the focus lays on developing the PE itself, not the immediate surroundings.

Consider how a material will change or 'age' after many years of use and sitting outside [67]. For example, will it get 'ugly' due to it changing its colour or dirty due to vegetation growth or mould. Choosing a material which rarely 'ages' can make it more suitable for reuse as it looks like a 'new' or barely used product.

Design for 'emotional durability' by creating (playground) equipment which can be personalised/ customized, as doing this can prolong the initial lifetime of a product [68,75]. The users or 'buyers' can create their own unique (to some extend) playground, and will, as a result, develop product attachment [70], which increases the willingness to repair, maintain and retain the PE, resulting in a longer lifetime. It can also create a competitive advantage and improved financial performance when product modularization is implemented [77]. Therefore, modularity should be implemented as it can further help to fulfil personalisation/ customization possibilities in PE design as well as facilitate several environmental benefits.

Effective implementation of the circular principles

As ‘product upgrade’ is an underdeveloped strategy in both product design [69,70,71] and playgrounds, it is difficult to make substantiated claims on its effectiveness. Therefore, ‘product upgrade’ is not an effective way to implement durability and should therefore not be implemented in the design of PE. However, as upgrading possibilities do promise product retainment in a theoretical sense, PSS and modular design (products consisting of various interchangeable modules), as recommended by van den Berge et al. [70], should be implemented in PE design.

Modular design should be implemented, as it creates many environmental benefits [79,80] and creates possibilities to integrate the effective parts of other strategies, such as ‘product upgrade’ and ‘personalisation/ customizability’. Furthermore, it is a widely used strategy in playground design, showing its potential and promise in the playground market.

Adaptable design should be implemented, as it anticipates and enables changes and adjustments that might be made to the product during its successive use cycles, which enables the possibility to cater for the different expectations and needs of its multiple users [90]. This serves to improve the PEs relevance in the future and thus avoid obsolescence [87,88], which is in line with conclusions from Hainess-Gadd et al. [68] and van den Berge et al. [70]. Furthermore, it can complement the earlier mentioned strategy of modularity by implementing configuration flexibility (demountable and movable components) and material reversibility (reusing secondary materials) [88].

6.1.3 Effective implementation of reuse

Reuse in playgrounds has mainly been implemented by means of reusing PE either on site or by acquiring them from playground depots. However, there are many obstacles associated with the reuse of PE from these depots [45]. Furthermore, as municipalities have a plethora of different PE [4] it is difficult to find the equipment you need.

Therefore, to effectively implement reuse in PE, a PSS strategy should be adopted. By maintaining ownership of the modular PE by the developer and performing maintenance and repairs the PE will stay in the highest possible quality, making them suitable for reuse.

Furthermore, instead of storing the PE in playground depots, the PE should be stored in a facility managed by the developer, thus again assuring the quality of the PE. By utilizing a PSS strategy, the PE developer can keep a clear overview of its PE. This in turn, allows for a better implementation of modular PE as separate modules can more easily be exchanged or taken back.

The lack of design for easy dis-assembly causes problems during maintenance. This is mainly due to equipment consisting of too many parts [46]. Thus, when the PE is modular and designed for easy (dis-) assembly, ‘neat dismantling’ can be realised [45,102,103,248], as “the way we design products determines how well they are suited for future recovery scenarios” [111]. This decreases the possibility of damaged or unusable PE. Because of this, modules could be exchanged between locations or transported to a new location without the need for extensive refurbishment.

Several drawbacks of a PSS system were expressed but are mainly related to the municipalities attitude and approach towards calling for tenders. This will further be discussed in chapter 10 Recommendations.

6.1.4 Effective implementation of repair & maintenance

Repair & maintenance have already been implemented extensively by several playground (equipment) developers, as successful repairs extend the lifetime of PE, maximizing its retention of value. Furthermore, effective maintenance also improves the play experience as it minimizes injuries caused by damage or faulty PE [105]. Both special maintenance services, regular check-ups or the employment of an external party have been explored and utilized. The main issue through all of these methods being the conformity of the PE design to perform effective maintenance. Therefore, to further implement repair & maintenance more effectively, the following must be considered.

As was discussed in paragraph 3.2, maintenance, repairability, and end-of-life challenges, particularly concerning inefficient disassembly during maintenance (due to equipment consisting of too many parts) and difficulties in repairing plastic and wooden parts, highlight significant obstacles [42,43,44,45,97]. Therefore, the PE should consist of a durable mono-material which already eliminates most of the repairs as it is resistant to wear and tear or damage. Furthermore, the PE should be designed with a material which, should damage occur, is easy to repair.

Also, the connection system of the PE should be made with a minimal number of parts and materials and be designed to simplify the (dis-) assembly process. This reduces difficulties that arise during playground maintenance, i.e. reaching possible problem (damaged) areas, and by doing so reduce material use, energy use and carbon emissions. This will also facilitate ‘participation in maintenance’ as the maintenance procedures are simplified which allows parents, teachers and concierges to participate.

Effective implementation of the circular principles

Participation in maintenance should be implemented as it creates a feeling of togetherness [4] but also lets owners or users take care of their PE, creating even more of an emotional attachment, as described by van den Berge et al. [70]. Also, this will speed up the maintenance process, decreasing the possibility of damage making the PE dangerous or unfit to play on, as municipalities are not able to perform maintenance in a timely manner [108]. Therefore, social workplaces should be employed, also to facilitate Social Return.

6.1.5 Effective implementation of refurbish, remanufacture & repurpose

Refurbish in PE has already been effectively implemented by playground (equipment) developers, by offering services, such as the Playcycle-certificate, to refurbish used PE. Playground depots also offer this service but are less effective in offering ready-to-use equipment [45].

Repurpose in PE is implemented by means of reusing waste, such as sewer pipes, to be used as PE. However, to further implement repurpose more effectively, it should be part of the overall design of the PE. Namely, if the PE modules are designed with multiple play functions in mind, it can be used in several ways throughout its many lifetimes (due to reuse). For example, a bicycle ramp in one playground could be repurposed as a climbing element in another.

Due to limited knowledge on remanufacture in existing product and PE design, this principle should not be implemented in PE.

6.1.6 Effective implementation of recycle

Recycle in PE has not specifically been implemented. Some playgrounds are made from recycled materials, but not many playground developers describe recycling options for their own equipment.

It is important to find a way to efficiently recycle the equipment at its definite end-of-life, preferably after it has been reused several times, as this is an important step towards circularity, in order to retain the remaining value of a product and its materials (as opposed to incineration for energy generation or discarding it on the landfill). Therefore, to implement recycle more effectively, every aspect of the PE, to make recycling of these materials worthwhile, should be considered: Choose appropriate materials which can be efficiently recycled, with recycling taking place in the Netherlands and results in low energy use and carbon emissions.

6.2 Design considerations contributing to increased outdoor play, physical activity and wellbeing among children

Several design considerations can contribute to increase outdoor play, physical activity and wellbeing among children, and will be discussed in this paragraph, thus answering sub-question 3.

6.2.1 Theoretical approach

More collaboration between the PE developer and the municipalities is needed, to create more engaging and challenging playgrounds, which increases outdoor play. Instead of designing for, the PE developer should be designing together with the municipality and discuss the important circular changes that need to be made. Furthermore, it is just as important to design together with children, as they are the prime user. Therefore, the PE was partly designed with children.

Inclusive playground design can both increase the outdoor play and wellbeing among children with a disability. Nonetheless, this has not been considered in the proposed PE design, as this was outside the scope of this project. However, recommendations will be discussed in chapter 10.

Detachable and moving (modular) playground equipment can offer a lot of variety both in play functions and exercise possibilities (exercise all muscle groups) [39,42,44]. Offering variety in playgrounds is important to develop circular PE, as children have a need cycle of 7 years [4]. Furthermore, by doing this you can cater for the different expectations and needs of its multiple users, which is in line with conclusions from Oost-Mulder & Van Weert [4], Hainess-Gadd et al. [68], Khan et al. [69], Van den Berge et al. [70] and Selvefors et al. [90].

Furthermore, playgrounds need to shift from overly safe to adventurous and offer lots of variety, which encourages children to play outside more [4,5,39,40].

The PE has been designed without a specific theme (pirate ship, castle, etc.) to encourage children to use their imagination and play with the equipment as they please [2,269].

Climate-smart playground design can both increase outdoor play and the wellbeing among children as they are less affected by the burning sun. Nonetheless, this has not been considered in the proposed playground equipment design, as this was outside the scope of this project. However, recommendations will be discussed in chapter 10.

6.2.2 Playtime observations

I observed playing children during outside playtime (Figure 57) to conclude on the preferred activities during playtime, as well as their behaviour towards certain PE. This chapter will discuss the results from these observations.

Playground equipment on site

The following playground equipment could be found on the playground (Appendix E): Climbing bench, ping-pong table, net swing, tumble bar, sitting wall, 2 climbing parkours, climbing caste + slide and monkey bars.

Most observed playtime activities

The activity that the children engaged in the most is soccer. Both a specially constructed soccer field with goals, as well as a big open playground space allowed for a range of ballgame-based activities. Both boys and girls engaged in playing soccer (Appendix G, page 140).

The open space also allowed for running and playing tag, which was another often-observed playground activity (Appendix G, page 138).

The tumble bars were occupied through the whole playtime. Both boys and girls engaged in tumbling and performing tricks (Appendix G, page 136).

Several parkour elements and a climbing castle allowed the children to engage in a lot of climbing, which was another activity that the children often engaged in (Appendix G, page 137).

Swinging on the net swing was another popular playtime activity (Appendix G, page 135).

Figure 57: Playtime observations

6. Results

Design considerations contributing to increased outdoor play, physical activity and wellbeing among children

Interesting take-aways

When children hang out, they often use elevations such as benches and climbing elements. The ping-pong table was used to both sit and stand on during the activity 'hanging out' (Appendix G, page 139).

This was also visible in January when it had been snowing, which created a patch of compact snow/ ice in the corner of the playground. The children enjoyed just hanging out on this newly created and exciting part of the playground, without engaging in any active activity (Appendix G, page 138). However, even though these slippery elements can be fun, it is also dangerous. Multiple children fell and some were hurt mildly.

The playground did not include any playhouses or close quarters. Therefore, multiple children used the garbage containers and ping-pong table as a place to hide or play house (Appendix G, page 135).

Playing soccer was more popular on the playground than on the allocated soccer field. The children preferred to just kick the ball around while it bounced of the different PE.

The main take-away among these observations is that children use objects on the playground in their own way to accommodate their specific needs. This was also visible when children played on the climbing equipment. A rope on the side of a walking bridge, intended to be used as support, is used as a tumbling bar (Figure 58). Here you can see the need for new challenges, as this new tumble bar is higher and wider than the actual tumble bars on the playground.

The wooden poles, as can be seen in Figure 59, are designed to manoeuvre around, not climb on. This is not allowed as it exceeds the maximum fall height for a concrete or stone catching surface (this will be further explained in paragraph 7). However, children will always find the limits of PE and they should therefore be designed with this in mind to prevent accidents.

6.2.3 Context mapping- and design sessions

I performed a context mapping and design session (Figure 60) to conclude on which play functions and PE, according to 80 children aged 8-10, would encourage children to play outside more. These sessions were also performed with 27 children aged 6-7 and 24 children aged 10-11 to see if there is a difference between these age groups. This chapter will discuss the results from these sessions.

The first exercise made the children aware of the context 'playing outside'. Furthermore, I investigated if a relation exists between their perception of outside play and their playground solutions of exercise 3. Pictures of the exercise sheets can be found in Appendix H.

Figure 58: Rope used as tumble bar

Figure 59: Wooden manoeuvre poles

Figure 60: Talking about one of the playground designs with the class

How do children perceive playing outside?
When asked about their experience with playing outside, children aged 6-11 mainly drew pictures of PE. The main location for their outside play is the schoolyard, a neighbourhood playground or their, or a friend's, garden (to play on the trampoline for example). They mostly play with friends or children next door.

Table 2 displays the number of times play functions were drawn or mentioned in exercise 1 'experience gatherer' by children aged 8-10, as an answer to the question 'What is your experience with playing outside?' The accompanying drawings can be found in Appendix H.

As can be concluded from this table, playing soccer is an activity that is performed by at least 25% of the 80 participants aged 8-10. This corresponds with the observations.

16% of children drew a wide range of playground equipment, many of which are present on their schoolyard. All other play functions mentioned, besides 'jumping on the trampoline', 'playing in nature' 'playing in neighbourhood' and 'other' could also be performed on their schoolyard. This indicates that the children mainly think of their own schoolyard when asked about their outdoor play experience.

The answers of both the children aged 6-7 (Appendix L) and 10-11 (Appendix O) are quite similar to the answers from the age group 8-10 regarding the expressed play functions, as can be seen in Tables 3 and 4. Sliding and swinging was drawn several times, as well as jumping on a trampoline. Interesting to note is that playing soccer was expressed a lot in the age group 8-10, while this was not the case in the other age groups. On the other hand, climbing was drawn a lot more.

Furthermore, children from the age group 6-7 also indicated that they think of 'playing in a sandbox', which was not expressed by the older age groups. Children in the age group 10-11 also thought of 'using the cableway' and 'playing shop/ 'cooking', which was not expressed by the other age groups. The 'playing shop/ 'cooking' activity mainly relates to a wooden structure on the playground which resembles a market stand. This equipment is mainly used by the older age group of the school, which is probably due to it being too high for the younger children (they cannot reach the tabletop).

This first exercise indicates that each age group has an overall similar perception of 'playing outside', while some play functions differ depending on the age group.

The second exercise of the context mapping session helped the children identify the problem. Their contributions can be found in Appendix I, M and P.

Table 2: Mentioned play functions context mapping session exercise 1 age group 8-10

Play function	Number of times mentioned
Playing soccer	21
Wide range (of equipment)	13
Swinging	10
Jumping (on trampoline)	8
Tumbling (tumble bars)	5
Sliding	5
Climbing	4
Playing on schoolyard	4
Playing in nature	4
Playing in neighborhood playground	3
Playing on climbing castle	3
Other (playing volleyball, BMX, talking, etc.)	10

Table 3: Mentioned play functions context mapping session exercise 1 age group 6-7

Play function	Number of times mentioned
Sliding	7
Climbing/ playing in treehouse	6
Swinging	4
Jumping (on trampoline)	3
Playing in sandbox	3
Playing soccer	2

Table 4: Mentioned play functions context mapping session exercise 1 age group 10-11

Play function	Number of times mentioned
Climbing/ playing in treehouse	10
Sliding	9
Swinging	5
Jumping (on trampoline)	4
Playing soccer	4
Using cableway	4
Playing shop/ 'cooking'	3
Doing water parkour	2

According to children aged 8-10, how can playgrounds/ playground equipment be optimized to encourage children to play outside more?
When asked to design a playground/ PE which encourages children to play outside more, the children concluded on the play functions (cards) summarized in Table 5 (scores under 8, based on play function cards, are not included). Their contributions can be found in Appendix J.

As soccer, climbing, skating, BMX and free running could be picked multiple times among the different themes, their scores have been summed up, of which the total score is presented in Table 5. Climbing can be selected a total of 4 times among the different pre-determined themes, which is the most of all play functions (for example, playing soccer, free running and BMX/ cycling can be selected a total of 2 times among themes). This might have resulted in the overall highest score and could be perceived as a flaw in the model. However, only 2 out of 80 children picked 2 climbing cards. Therefore, the children unanimously decided their playground needed some form of climbing.

Besides the play function cards, the drawings were also examined to retrieve recurring play functions and see if there is a consensus among the cards and drawings (Table 5). As can be concluded, the chosen play function cards and drawings are similar and therefore complemented each other. As a result, no additional play functions were derived from the drawings.

As a last exercise the children had to vote on the ideas which they thought would encourage children the most to play outside more (Appendix K). The chosen cards and drawings were again quite similar, also regarding the overall score. Climbing playgrounds were chosen the most, as 8 out of the 13 best rated playground designs had big climbing structures, which were portrayed as for example a castle or a tree house.

To conclude on the design session all scores were summed up to find the resulting ranking of the play functions. However, just summing up the found values might not provide a fair and accurate representation of which play function has been chosen the most to be implemented in the designed playground. To avoid potential bias from the overlap, a weighted scoring system is applied. Total score 2 will be divided by 10 and added to 1. This created 'winning' factor is multiplied by total score 1. Total score 3 is the resulting value and determines the end score for each of the 10 play functions (Table 5).

Table 5: Mentioned play functions design sessions 1-4 age group 8-10

Rank	Most frequently chosen play functions (cards)	Total number of times chosen	Most frequently chosen play functions based on drawings	Total score 1	Most frequently chosen play functions based on highest score (play function cards)	Most frequently chosen play functions based on highest score (drawings)	Total score 2	Total score 3
1	Climbing	37	19	56	9	8	17	151,2
2	Playing soccer	19	22	41	2	4	6	65,6
3	Swinging & swaying	10	14	24	2	6	8	43,2
4	(Roller) skating	17	10	27	2	2	4	37,8
5	BMX	15	7	22	3	3	6	35,2
6	Free running	14	12	28	1	1	2	33,6
7	Playing in treehouse/hut	12	15	27	1	1	2	32,4
8	Sliding	8	10	18	2	3	5	27
9	Fitness	11	9	20	1	1	2	24
10	Scavenger hunt/ maze	8	3	11	3	0	3	14,3

According to children aged 6-7, how can playgrounds/ playground equipment be optimized to encourage children to play outside more, when compared to children aged 8-10?
When asked to design a playground/ playground equipment which encourages children to play outside more, the children concluded on the play functions (cards) summarized in Table 6. The preference for certain play functions was more divided, resulting in several being chosen only once or twice. Therefore, scores under 3, based on play function cards, were not included. The contributions of the children can be found in Appendix N.

Overall, the chosen play functions are quite similar between the two age groups, as out of the top 10 they share 7. Swinging & swaying and (roller) skating are both high scoring play functions.

On the other hand, playing soccer was chosen much less, which might be because this younger age group has not yet found such a fascination for soccer which was the case for the older age groups.

Climbing was also chosen less, which might be because this younger age group is still a bit nervous about climbing certain heights.

Table 6: Mentioned play functions design sessions 5 age group 6-7

Rank	Most frequently chosen play functions (cards)	Total number of times chosen	Most frequently chosen play functions based on drawings	Total score 1	Most frequently chosen play functions based on highest score (play function cards)	Most frequently chosen play functions based on highest score (drawings)	Total score 2	Total score 3
1	Swinging & swaying	8	7	15	1	2	3	19,5
2	Jumping on trampoline	8	4	12	2	1	3	15,6
3	Roller skating	8	3	11	3	1	4	15,4
4	Playing in treehouse/hut	5	6	11	1	0	1	12,1
5	Climbing	3	6	9	1	1	2	10,8
6	BMX	4	2	6	3	1	4	8,4
7	Playing soccer	3	3	6	2	2	4	8,4
8	Sliding	5	1	6	0	0	0	6
9	Dancing	3	0	3	1	0	1	3,3

Table 7: Mentioned play functions design sessions 6 age group 10-11

Rank	Most frequently chosen play functions (cards)	Total number of times chosen	Most frequently chosen play functions based on drawings	Total score 1	Most frequently chosen play functions based on highest score (play function cards)	Most frequently chosen play functions based on highest score (drawings)	Total score 2	Total score 3
1	Climbing	13	12	25	6	10	16	65
2	Playing in treehouse/hut	12	11	23	6	7	13	52,9
3	Swinging & swaying	4	5	9	2	5	7	15,3
4	Playing soccer	4	7	11	0	0	0	11
5	BMX	5	4	9	1	0	1	9,9
6	Scavenger hunt/ maze	3	4	7	1	1	2	8,4
7	Dancing	3	2	5	3	2	5	7,5
8	Free running	3	2	5	1	2	3	6,5

A big difference between the two age groups is that the younger age group chose 'jumping on a trampoline' quite often, while this is not the case for the older age group. However, as the PE design, as proposed in this thesis, will not include a trampoline as it does not fit the scope of the project, this was ignored.

According to children aged 10-11, how can playgrounds/ playground equipment be optimized to encourage children to play outside more, when compared to children aged 8-10?
When asked to design a playground/ playground equipment which encourages children to play outside more, the children concluded on the play functions (cards) summarized in Table 7 (scores under 3, based on play function cards, were not included). The contributions of the children can be found in Appendix Q.

Overall, the chosen play functions are again quite similar between the two age groups, as out of the top 10 they share 7. Both age groups had a high preference for swinging & swaying, playing soccer and BMX, with climbing being the top 1 for both groups.

On the other hand, playing in a treehouse/hut was chosen more among the older age group, as well as the younger (6-7) age group, indicating that such preferences are probably more individually, or group based and not based on age.

Parallel academic literature, observations and design sessions

A parallel can be found between academic literature and the results from the design sessions. Both confirm that climbing and swinging & swaying (in a broad sense) [259,260,261,262,263,264,265,266] are frequently-used and sought-after play functions among children. Furthermore, both, together with the conclusion from the municipal meeting, express the desire for risky play [267,268], which was expressed by the children as they preferred climbing, swinging & swaying, skating, BMX and free running.

Implementation of results in PE design

As a result, I included the play functions climbing, swinging & swaying and free running in the design of the PE, and also focused on risky play, as it allows children to skate or BMX. These are both wanted play functions and contribute to the physical and mental wellbeing of children, which is in line with the social aspect of sustainable design.

Furthermore, I included another highly desired play function 'playing in a treehouse/hut', to create a contrast between active/ risky play and 'hanging out'. Having both active and passive areas in the playground encourages different types of children to play in the playground.

As I concluded from the playtime observations, children use objects on the playground in their own way to accommodate their needs. Therefore, I designed the PE to be abstract (with no obvious theme) but with multifunctionality to accommodate for multiple play activities and imaginative play [2,269].

Even though soccer is a well performed and sought-after play function, no specific goals or soccer field will be included, as children can play soccer anywhere, as was concluded from the observations. However, to accommodate for playing soccer, and games related to this like shooting penalties, indications of goals (wide space between poles or structures) will be integrated into the design.

Comprehensive playground directions

The play functions are divided into 'comprehensive playground directions' and derived from the reflexive thematical analysis. These create a more free-to-interpret approach towards the development of the PE and will serve as inspiration, with the main premise being 'adventure and excitement'.

Treetop Retreat
Climbing and 'play in treehouse/ hut' translates to having your own space high up where you can relax or hang out with friends.

Rapid Rush
Skating, BMX/ cycling and free running translates to 'moving fast' and excitement.

Acrobatic Adventure
Climbing, free running, swinging & swaying and scavenger hunt/ maze translates to moving through and over a parkour.

Hideaway Hunt
'Scavenger hunt/ maze' and 'play in treehouse/ hut' translates to a great game of hide and seek or finding an imaginative treasure.

6.3 Implementation of design considerations in the PE

Several design considerations have been addressed in chapter 4 (based on the material) and paragraphs 6.1 and 6.2. In this paragraph, I will discuss how they are implemented into the design of the PE, as described in this thesis.

Some design considerations, as discussed in paragraph 6.1 and 6.2, are promising to effectively implement the circular design strategies into playgrounds. However, these were not implemented due to time limitations, prioritization and falling outside of the scope of the project as described in this thesis.

Create an interchangeable and customizable system with components that are easy to (dis-)assemble (PSS with modular play modules)

I designed the PE for adaptability, featuring various modular units that can be arranged in multiple configurations, providing a customized and unique playground experience. This modular design not only eases disassembly for relocation but also extends the PE's lifespan through potential reuse in different locations. Emphasizing configurational flexibility, the PE anticipates and accommodates changes and adjustments throughout successive use cycles, ensuring it meets the evolving expectations and needs of diverse users. This forward-thinking approach enhances the PE's relevance over time, mitigating the risk of obsolescence.

In addition to adaptability, the PE prioritizes 'emotional durability' by allowing users to personalize their playground through modular equipment. Users can select specific play functions by arranging modular elements in diverse configurations. Offered through a product-service ystem, the modular PE empowers clients to mix-and-match modules, creating a unique playground tailored to their preferences. This system facilitates easy module exchanges, enabling users to replace only the necessary parts based on changing play functions or evolving needs. Moreover, modules can be swapped between playgrounds or returned to the developer, promoting a sustainable cycle of reuse.

Design with a mono-material

The PE will be made from mostly Geopolymer, with the addition of bamboo. By creating equipment which consists of a mono-material, the need for different materials, and thus the production of these, is reduced. Furthermore, recycling of these parts becomes more efficient, as no additional separation of materials is needed.

Design with a material which comes from a waste stream

Material reversibility is achieved as the PE is made from a secondary (waste) material; Geopolymer, which can also be efficiently recycled to create new products of the same material. As a result, circularity of the material is achieved.

Design with a material which allows for form freedom

The PE will be mainly made from Geopolymer, as this material can be processed into a wide variety of different shapes and sizes.

Furthermore, the production method to produce the PE is 3D-printing, which allows to create interesting shapes by only applying material where it is needed, i.e. the PE will be mostly hollow which reduces the weight and the amount of material used in a single PE module.

Design with a material which is resistant to wear and tear and external conditions (cold, heat, moist, UV radiation, etc.)

Considering the behaviour of the material and making design decisions accordingly can decrease damage to the overall structure over time, thus prolonging its life. Therefore, this has been considered. Geopolymer has been chosen, which is not affected much by changing weather conditions.

As Geopolymer is a very strong material, it will rarely get damaged by transport from one location to another, ensuring reuse possibilities.

The aging of several materials, due to weather conditions, such as moist and UV radiation, has been compared (Appendix D.6). Geopolymer does change its colour due to UV radiation but does not age so significantly as for example wood.

Eliminate redundant elements

By creating protrusions and recessions into the main structure of the Geopolymer playground equipment by means of 3D printing, there is no need for additional grips or the post-processing of recessions.

Design PE modules which can fulfil multiple play functions

The PE modules are designed so that they can fulfil several play functions, also by being able to configurate them with several other modules, allowing the PE to be used in multiple ways, which facilitates imaginative play. This also allows the modules to be repurposed in the same or a different playground.

Design a connection system which allows for easy (dis-) assembly and consists of a minimal number of parts and different materials

The Geopolymer modules are shaped in a way that they can be stacked on top of and next to each other, already facilitating a form of connecting. To further secure the modules together I designed a connection system which needs a minimal number of parts and uses the bamboo as part of the connector, eliminating the need for additional connectors. Furthermore, as the connection system is easy to reach and manage the (dis-)assembly procedure is simplified which allows for neat dismantling.

A more elaborate explanation of the connection system can be found in Chapter 7.

Design for effective and minimal repairs and maintenance

As the PE modules are mostly only a 'piece of 3D-printed Geopolymer' maintenance becomes very easy as there is no need to disassemble a lot of different parts, making it easier to reach the damaged areas. Furthermore, knowledge and material is only needed to repair this one material, which is relatively easy to do as well. If a piece of the Geopolymer is worn or broken of it can simply be repaired by applying new soft geopolymer, which after it hardens is as good as new.

Design with materials which can efficiently be recycled

Geopolymer can be efficiently recycled. During recycling, large and small Geopolymer and TC structures are reduced to its original components (sand, gravel and crushed stone) in a tumbling machine, of which most can be reused in a new Geopolymer or TC product. Therefore, there is no need for new recycling methods or plants, as Geopolymer can be recycled together with TC.

Furthermore, recycling and production of the Geopolymer can be realised in the Netherlands, which has a positive effect on the transport of materials and products.

Design PE which increases outdoor play and physical activity

I designed the PE to include the play functions climbing, swinging & swaying and skating, among others, with a focus on risky play, as these are both wanted play functions and contribute to the physical and mental wellbeing of children, which is in line with the social aspect of sustainable design. Four directions have been developed: 'Treetop Retreat', Rapid Rush', 'Acrobatic Adventure' and 'Hideaway Hunt', which all encompass several of the desired play functions as retrieved from the design sessions (Paragraph 6.2.3). These directions will be incorporated into the PE design.

The assignment of the project within this thesis is to develop C&S PE. After conducting research to answer the research question and sub-questions, I derived design considerations and other relevant conclusions from this and used these insights to design the modular Geopolymer PE.

In this chapter I want to discuss the different considerations and choices that I made regarding the design, like the shape, size, colours, connection mechanism and the implementation of the design considerations as discussed in paragraph 6.3.

7.1 Design process

In this paragraph I will discuss my design process and studies (inspiration boards, colours, shapes, mechanisms, etc.). The choices that I made were concluded into a final design proposal which will be discussed in paragraph 7.3.

3D-printing of Geopolymer

During the visit to Weber (paragraph 4.7.1.) I already got a good insight into the possibilities of 3D-printing. However, to find out what else is possible with Geopolymer 3D-printing, I conducted a study on this (Appendix R). This study helped me to conclude on which play elements could be implemented in a 3D-printed object and helped me to come up with several shapes (Appendix S).

Furthermore, I used the 3D-printing guidelines which were provided by Weber to construct a shapes which are 3D-printable (I will discuss this in more detail on page 51 and 52).

Moving and lifting the play modules

As the play modules have to be lifted and moved to configurate and stack them to form the PE, a choice has to be made on the method to do so. This is important as the way of lifting partly dictates the design of the play modules. Three methods are discussed here.

The first method is to use a clamp (Figure 61). As explained by P. Cornelissen [216] their 3D-printed products are lifted by means of such a clamp, which compresses the product tighter depending on its weight. A positive factor of this method is that objects can be lifted and moved in a straight manner, which is useful when stacking the play modules. A downside is that clamping could lead to the Geopolymer walls breaking when they are clamped wrong. The damage in Figure 49 on page 29 was caused by a lifting clamp. However, this rarely happens [216] and can be prevented by clamping the object on its flat side (Figure 62, left) rather than on the layered side (Figure 62, right).

Another method is to insert hooks into the Geopolymer. These can be connected to cables to lift the play module (Figure 63). However, as these hooks will stick out, this is not a preferred method when the products should be stacked. Furthermore, children might hurt themselves on these hooks.

The last method is lifting the module with a strong rope or band (Figure 64). A positive factor is that this minimizes damage (as opposed to clamping). However, for this method to be implemented the module should be hollow to fit the band through (which might not be the case for all modules) and additional assistance is needed to keep the module straight when lifted.

To conclude, as clamping is the most appropriate method to lift and move the modules, the design will accommodate for this procedure by having at least two flat sides.

Figure 61: Lifting concrete block clamp [273]

Figure 63: Lifting concrete block with built-in hooks [274]

Figure 64: Lifting 3D-printed concrete stairs [275]

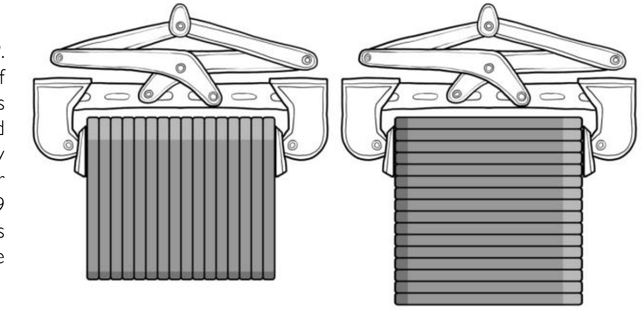


Figure 62: Clamping of a 3D printed object

Shape possibilities

The shape of the Geopolymer PE modules is very important, as it dictates the playability and invites children to play on them. During my visit to the DDW in Eindhoven, I was already inspired by stackable candle holders (Figure 65), which reminded me of modular playground modules. To further get inspired by shape and playability possibilities, a study on concrete PE and playable non-PE concrete structures was performed (Appendix T).

One conclusion that can be drawn from this is that concrete playgrounds are quite common and enjoyed by children all over the world. The most iconic being the 'hexagonal concrete blocks climbing structure' (Figure 66) from Aldo van Eyck which already exists for over 60 years, showing its durability. This design served as a source of inspiration for the developed Geopolymer PE. However, new concrete playgrounds are also being developed. For example, Studio Ossidiana worked together with students from the TUDelft to develop concrete playground structures in which they "expand the concept of the playground to the realm of the city by looking at urban spaces and elements (squares, arcades, stairs, bridges, urban furniture) as potential playful structures, that could stimulate imagination, creativity and interactions among citizens of all ages" [277], which is partly in line with the principles as discussed in this thesis.

As a design process is not linear, I also did research on the casting possibilities of Geopolymer, which can be found in Appendix U. Even though the PE will be printed and not cast, I still want to discuss the possibilities and consideration of casting Geopolymer, as it still inspired other design decisions. Because of this, I also worked on several ideas and sketches of casted Geopolymer PE structures (Appendix V).

To decide on the shape of the individual play modules I sketched out four shape ideas: Cube, Hexagon, Panel and Tetris. These ideas have been assessed based on a Harris profile [117] with requirements derived from the design considerations in 6.3 and my own design preferences. The shape sketches and evaluation procedure can be found in Appendix W.

I concluded from the Harris profile that Tetris shapes (Z-shape, L-shape, T-shape and Cube (Figure 67)) are the most appropriate for the modular PE. These various objects have several sides to which play elements can be added (protrusions for climbing, bamboo elements, etc.), and due to their shape allow for additional playability and various stacking possibilities in multiple directions. This creates unique, interesting and exciting PE. Therefore, the PE will consist of modular 3D-printed Geopolymer Tetris shapes.

Figure 65: Inspiration from DDW

Figure 66: Hexagonal concrete blocks climbing structure by Aldo van Eyck [276]

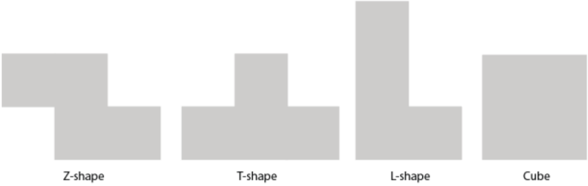


Figure 67: 4 PE module shapes

Safety requirements

In order to design PE which is in line with the appropriate regulations and guidelines, van Ee provided me with the relevant NEN-EN documents. The regulations in these documents were used to make design decisions which ensured that the PE is save to play on.

One relevant regulation is the 'free fall height' (vrije valhoogte), which is defined as the 'largest vertical distance from the clearly intended body support to the catching zone below it' (Figure 68) [278]. This fall height cannot be higher than 3000 mm (with additional protection such as railings) but also depends on the use of the PE and the material of the underground. For example, this is up to 0,6 metre on a concrete floor, up to 1 metre for a sand ground, and 1,5 metre or higher for natural grass or other shock-absorbent undergrounds, like wood chips or rubber [97].

Furthermore, the 'Common playground design issues' document by Play Australia [279] was also used to get well informed in terms of safety design. For example, something that is often overlooked are 'entrapment openings'; Openings which could lead to children getting their head stuck in between an opening [279]. Another important element, especially for the Geopolymer PE, are regulations around protrusions. Here, edges and corners on elements that are in locations in which a person could come into contact should have a minimum radius of 3mm. However, bevelling, etc. to eliminate sharp edges/corners will often be satisfactory [279], which is already the case with 3D-printed Geopolymer objects.

Size considerations

The NEN-EN-1_2017 served as the basis for identifying the size of the Geopolymer modules (Figure 69). Measurements of Dutch 12-year-old children, such as standing and squatting height, from Dined were used to conclude on the playability when compared to size. This age-group was chosen as this is the oldest (and tallest) group of children that the PE will be designed for. When an opening in the PE, to sit in, is roughly designed to accommodate for their size, other smaller children will also be able to fit. Furthermore, as the Tetris shapes have different heights and stair like elements the PE will accommodate for a wider age group to play on them.

The squatting height was taken into account to conclude on the size of open modules which allows the children to sit or hide in. The step-up height was also considered to conclude on the ability to climb/ walk on the modules.

As 1500 mm is allowed for a soft underground such as wood chips, the modules will have a 'layer height' of 480 mm so that 3 layers can be stacked. These different layer heights allow for different age groups to climb or step on them, almost creating various difficulty levels. Furthermore, because the height of the PE can differ, some are allowed to be placed on concrete (< 600 mm), some on sand (<1000 mm) and some on wood chips (<1500 mm) which allows for more freedom in configuration among the playground.

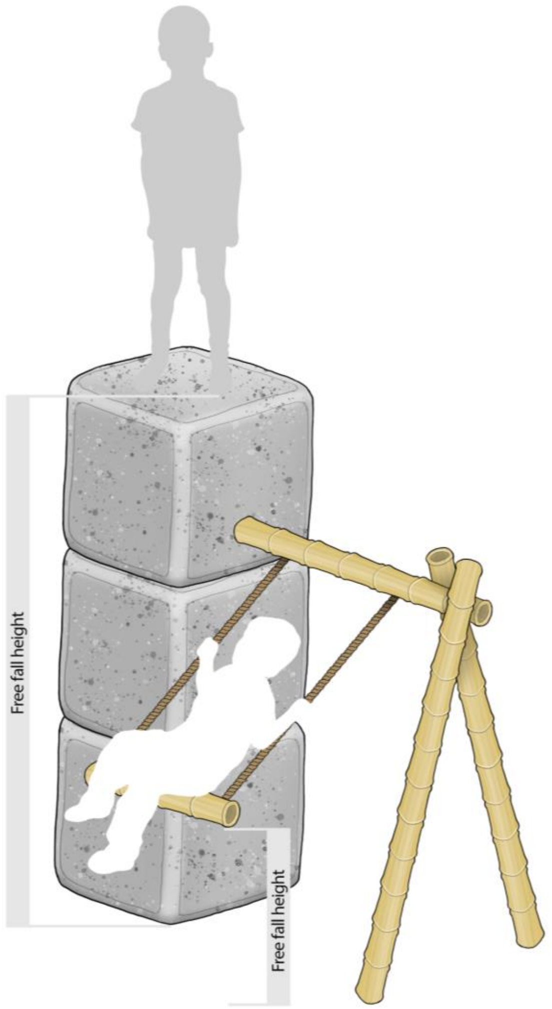


Figure 68: Fall height illustrated

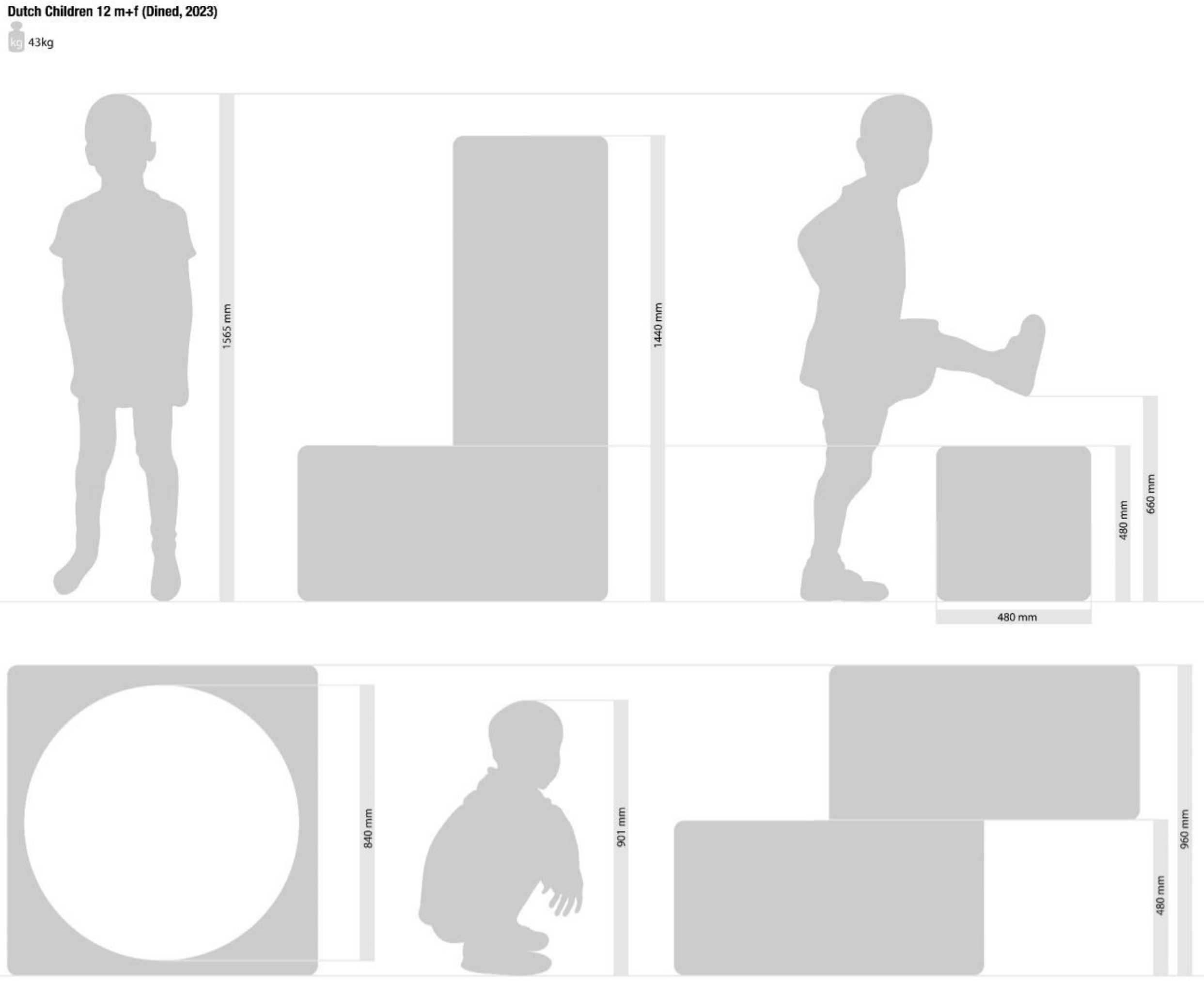


Figure 69: Size of PE Geopolymer blocks

Technical design of Geopolymer modules and connections

The Geopolymer Tetris-shaped play modules, which will be called ‘Geobam Play Blocks’ (or Blocks) from here on forth, need to be connected to each other and to the bamboo poles to form additional PE.

A mono-material connection could be the solution to developing a connection system which allows for easy (dis-)assembly and consists of a minimal number of parts and different materials. With this approach, no additional connectors are needed which also simplifies its repair and maintenance and allows for more efficient recycling as no additional parts need to be separated.

Therefore, I looked into several design directions which allowed the Blocks to be connected in this way and was also 3D-printable (Appendix X) and concluded on a jigsaw-like structure (Figure 70).

However, after further development I concluded that such a connection system is not favourable. Firstly, it allows the Blocks to be connected in only one direction (Appendix X). This would be a waste of the design of the Blocks as they are supposed to be configurated in many different directions, which is also preferred in the modular system as I envisioned it.

Even so, the jigsaw-like slots and protrusions obstruct the Blocks from being stacked in any other direction than the one that they were originally designed/ produced for. This again contradicts the approach of modularity. Furthermore, children could get caught behind the slots and protrusions and is therefore not safe to play on (Figure 71).

I therefore considered alternative mono-material connection designs, such as a ‘lego block stud’ connection or an additional Geopolymer swallow-tail connector which allows the Blocks to be connected in two directions (Appendix X). However, they all failed in the same way or were not able to be produced with 3D-printing.

Besides this, van Ee [280] raised concerns regarding the assembly of these Blocks with a jigsaw-connection, as the blocks need to be positioned perfectly straight in order to slide together, which would make assembly very time consuming.

For these reasons, I decided to not include a mono-material connection. Also, as I wanted to focus on modularity, where the Blocks can be configurated in as many ways as possible, I prioritized to design for this. However, I still wanted to design a connection which had similar principles as a mono-material connection in terms of refuse, rethink and reduce, repair and maintenance and recycle.

Therefore, I came up with the following design (Figure 72). The Blocks will be printed with an external silhouette shape and an internal structural framework made up of circles with an internal diameter of 65 mm (Figure 73) (technical drawings can be found in Appendix Y), through which bamboo poles will be inserted which will be used to connect the Blocks. This shape is designed according to the 3D-printing guidelines from Weber and verified with them [281]. I decided the structure needed both an internal and external framework, so that all the connections are constructed on the inside of the Block and the outside is smooth, which facilitates stacking. It also partially prevents playing children from interacting with these connections and prevents them from trapping their fingers or other body parts in between these slits (Figure 74).

I constructed two additional designs with a simplified framework (Figure 75), to decrease the needed amount of print material. However, after consultation with Weber we concluded that the original shape was most appropriate for printing [281].

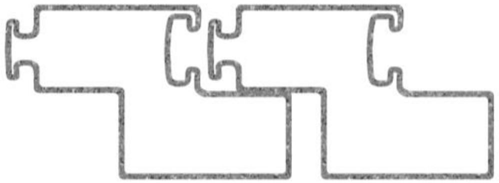


Figure 70: Jigsaw connection between Z-shaped modules

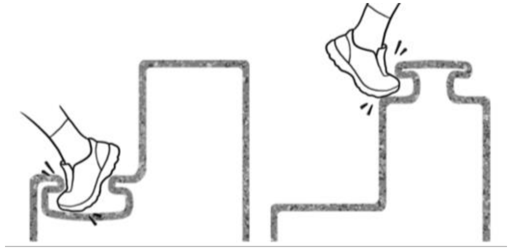


Figure 71: Tripping due to jigsaw slots and protrusions

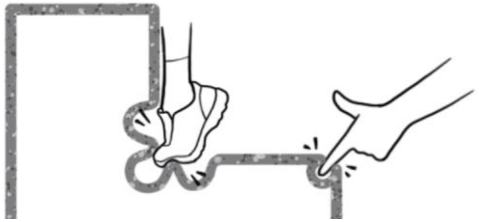


Figure 74: Entrapment due to open structural framework

7. Design

Developing the Geopolymer playground equipment

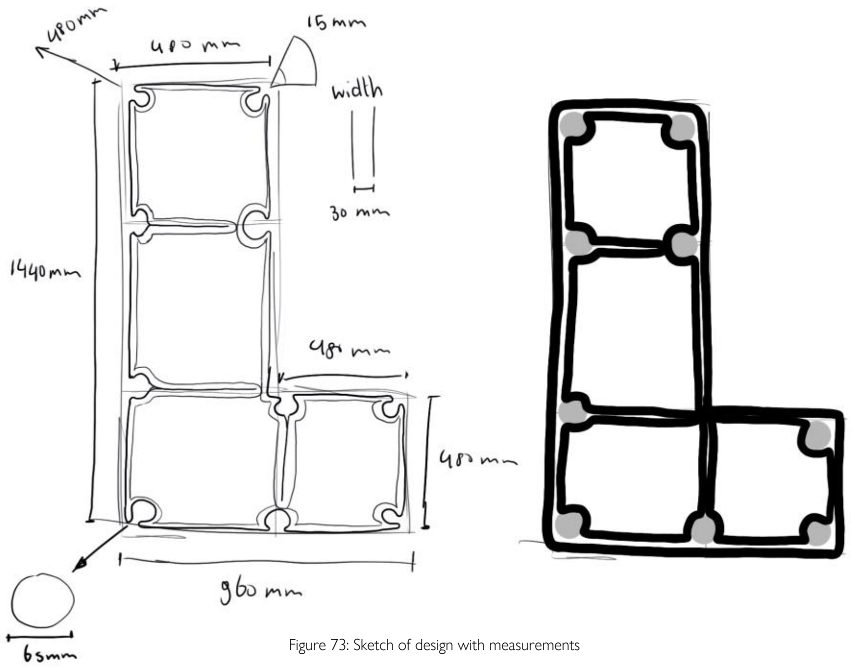


Figure 73: Sketch of design with measurements

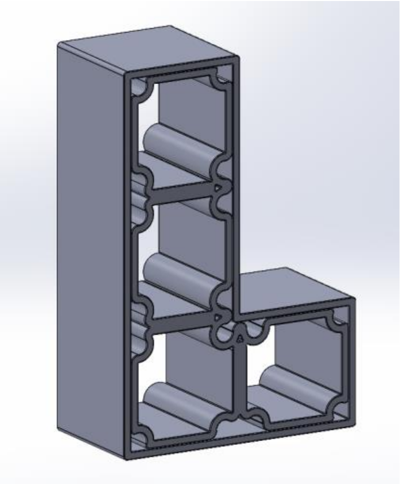


Figure 72: Design of the 3D-printed L-shape Geobam Play Block

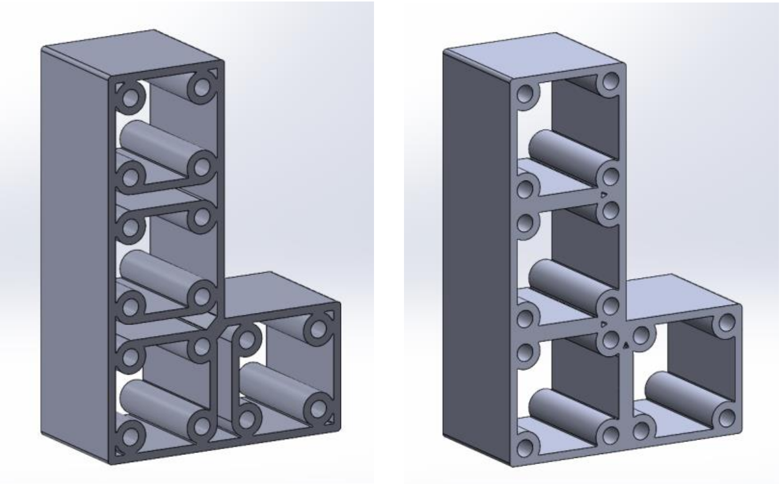


Figure 75: Alternative designs of simplified internal structural framework

The Tetris shapes already allow for 'connecting' the Blocks in a way where they can obstruct each other from moving or tipping over, especially due to their weight (Figure 76). However, as safety has a very high priority in playgrounds (we never want these blocks to fall over), I designed an additional connecting system.

To connect the Blocks, they will first be configured next to each other or on top of each other, depending on the needed shape and function. Then, a bamboo pole with a width of +-65 mm is inserted through the multiple holes and secured in place (which I will discuss in more detail in the next paragraph).

The length of these poles will vary from 480 mm up to 4000 mm depending on the needed function. Bamboo can be grown to different widths and lengths, far exceeding the 4000 mm that I need [282]. As bamboo is a natural product it does not have a perfect and similar width over the entire length though. Therefore, bamboo poles are often offered within a width range (for example, 50-60 mm). However, if needed they can be selected on a specific width [244], ensuring that the bamboo used in the Geobam Play Blocks playground always have the desired with.

I chose the width of +-65 mm as I wanted to find a balance between playability and strength. The bamboo poles used for connecting the Blocks together will mainly be used for holding them in place and need to carry the force of several children hanging from it. It does not need to carry the whole weight of the Geopolymer Blocks itself, which will already be partially done by its surrounding Blocks. Therefore, I did not need a very big width, especially when bamboo has a similar strength to steel [229,230,231]. Certain types of bamboo with a width of 50-60 mm are used for houses and other types of construction [283], which would be sufficient for my use-case.

To accommodate for playability, I looked at the width of steel poles for climbing and tumbling in playgrounds, which is usually around 35 mm [284]. However, I believe 35 mm to be too small for the bamboo poles to carry part of the weight of the Blocks. Therefore, I chose for an almost doubling of this width which I believe should be enough. Other bamboo poles within the playground will have a width of +-35 mm to allow children to climb on them.

However, to make a substantiated claim on the appropriate thickness of the bamboo, strength tests will need to be carried out. Nevertheless, due to the scope and allocated time of this project, as well as limited resources to perform such tests, these were not carried out. Still, as they are of importance to the structural integrity of the PE I want to discuss possibilities in paragraph 10 Recommendations.

Connecting the bamboo poles to the Geopolymer Blocks

To secure the bamboo poles to the Geopolymer Blocks I came up with several approaches. My initial idea was to add 'securing caps', made from bamboo to limit the number of different materials, to both ends of a pole (Figure 77). These securing caps would obstruct the bamboo from sliding out and the Blocks from moving. However, I eventually discarded this approach as:

1. Crafting an elaborate bamboo product results in the use of laminated bamboo with an adhesive or resin, which defeats the approach of using a bio-based material and results in additional production steps.
2. The bamboo poles would stick out, which I did not like aesthetically, and children can reach it more easily.
3. The rings at both ends allow the pole to rotate, which is dangerous and causes the bamboo to wear down inside the Geopolymer tube.

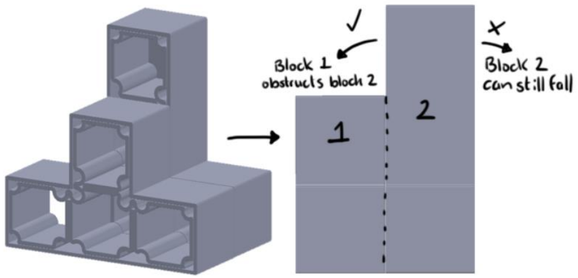


Figure 76: Prevent moving and tipping over due to obstructing Blocks and weight

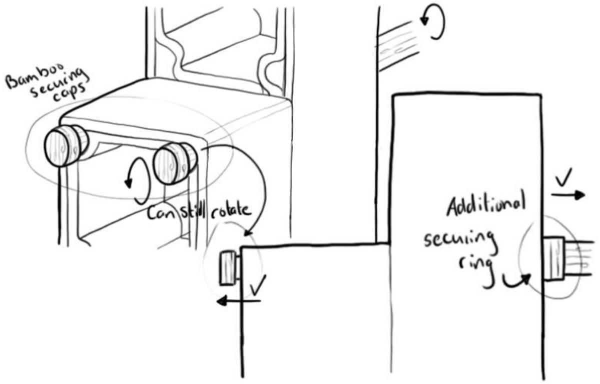


Figure 77: Bamboo securing caps secured to bamboo pole between two Blocks

I also considered securing the bamboo to the Blocks with bolts, as they are a widely used bamboo connector (Figure 78). However, a bolt connection can cause several structural problems [286,287]:

1. The bamboo is more prone to splitting as material is removed to put the bolt through, thus creating a weak spot.
2. In bolt connections, often a large single fastener is used which has to carry all the loads. Due to the large bolt, the created pre-drilled hole needs to be bigger (thus more material is removed).
3. It is difficult to align the bolt holes which could cause the bolt to be placed slanted into the bamboo pole. This could result in both sides of the bolt carrying an unequal load, which increases the chance of structural failure.

Using a screw connection solves these issues, among providing several other benefits [287]:

1. Self-drilling screws eliminate the need for pre-drilling a hole. They only remove a limited amount of material and are secured within the bamboo, creating a tight fit, preserving the structural integrity.
2. A screw connection would include several small-diameter screws, as opposed to the single bolt fastener. This enhances robustness against splitting, as the multiple screws can more easily redistribute the load in the case of an unforeseen loss of one or more individual fasteners.
3. Screw connections are more ductile and stiffer than bolted connections. A high ductility, which is a measure of a structure's ability to undergo large deformation before strength loss, is important for the PE as deformations will be caused by children playing on the PE and specifically the bamboo poles.
4. Screw connections have the advantage of easier disassembly.

Therefore, I chose to secure the bamboo to the Blocks with self-drilling lag/coach screws. To create a structural sound connection system, which further increases splitting, I also incorporated the design considerations from Malkowska et al. [287]:

1. If sufficient spacing is provided and the screws are staggered, the ductility is increased, and splitting becomes rare.
2. Screws should be made of stainless steel to increase ductility.
3. The premise of environmental benefits is only true if the amount of steel is minimized. However, the connection stiffness increases linearly and proportionally to the number of screws, at least up to 4 screws.

As a result, each pole will be secured in a staggered configuration to the inner tubes of each individual Block with 4 stainless steel, self-drilling lag/coach screws (Figure 79). A hole will be drilled through the Geopolymer, and due to the design of this specific screw (Figure 80), is only screwed into the bamboo. Therefore, no thread is created into the Geopolymer which allows for replacement of these screws, similar to bolts, without the need for drilling new holes (Figure 80).

Figure 78: Bamboo bolt connection [285]

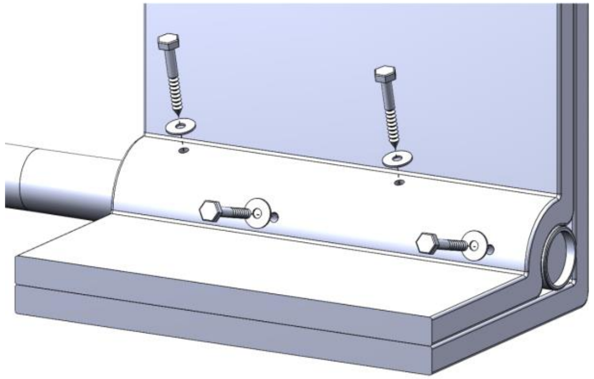


Figure 79: Hole and screw placement

Figure 80: Section view of screws through Geopolymer and screwed in bamboo

Developing the Geopolymer playground equipment

The screw connection holds the bamboo in place, prevents it from rotating when children are swinging on it and holds the Blocks together. It also allows the Blocks to be configured on top of- and next to each other with the open sides and printed sides touching (Figure 81), and perpendicular (Figure 82), which is preferred in the modular system as I envisioned it.

The Blocks can be connected in the perpendicular direction by using bended bamboo poles, which is already applied in bamboo structures and furniture (Figure 83). Bending a bamboo pole can be done with three methods: laminating, heating and kerfing. With kerfing, slits are carved into the bamboo, which is the quickest method but does leave the material in a weaker condition. Bending with heat is the best method, as it doesn't weaken the material drastically and avoids altering the state of the material [289].

As the Geopolymer modules are quite heavy, they are not required to be secured to a foundation. However, to make sure the modules cannot tip over when multiple children are hanging on it, a construction rule will need to be instilled: The width of the lowest layer of cubes of a play element should always be at least 1/2 of the height of the play element (Figure 84), which was verified by van Ee to be a sufficient measure [280].

Implementing refuse, rethink & reduce, maintenance, repair and recycle
Another great function of this connection system is that bamboo poles, and play elements made from these bamboo poles, such as monkey bars, can be connected to the Blocks by means of the same internal structural framework (Figure 85), eliminating the need for additional connectors, such as bamboo clamp connectors [290]. Furthermore, as the connection system makes use of bamboo, which is already used as an integral part in the PE, I eliminated the need for additional materials.

Moreover, repair, maintenance and disassembly are still simplified as the connecting bamboo poles can easily be slid out from the Blocks once the screws are unscrewed. The screws will 'damage' the bamboo, but this is not a problem as the bamboo will be replaced after extensive use anyways. As the Blocks are hollow, these screws are easily accessible for maintenance or replacement.

This disassembly approach also helps with the recycling step. The bamboo needs to be removed from the Geopolymer Blocks before these blocks can be moved or lifted. Removing the screws is easy, and because they are not screwed into the Geopolymer they will seldom be left behind in the Geopolymer. Therefore, all three materials are easy to disassemble. The Geopolymer Blocks and screws can be reused or recycled, and the bamboo can be incinerated where part of its energy is recovered.

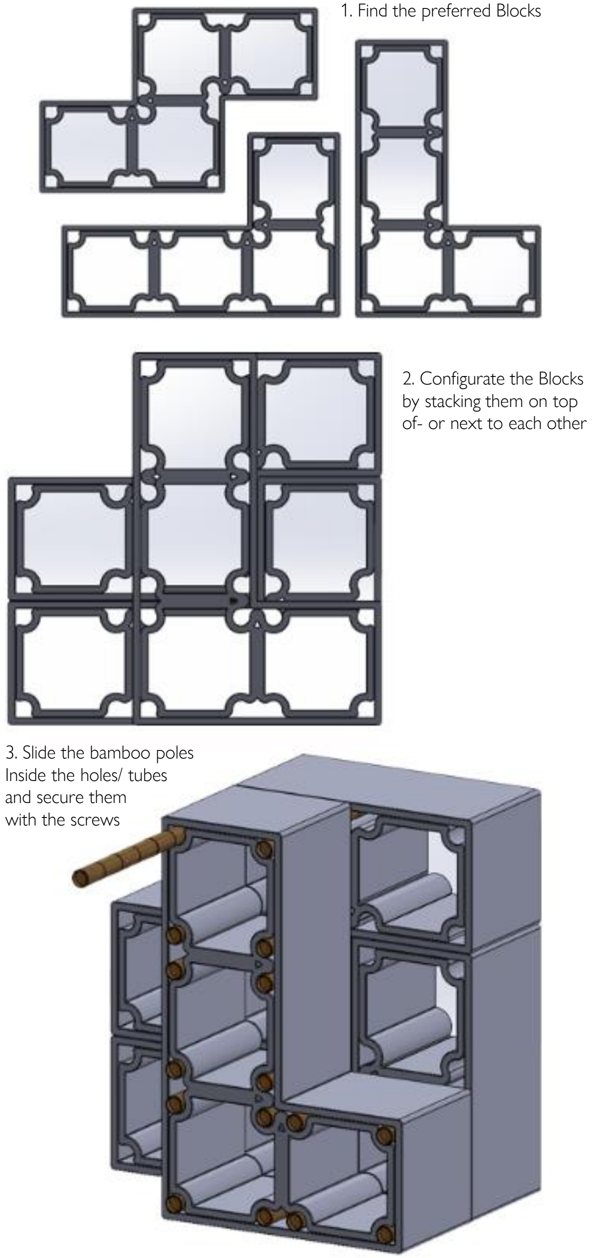


Figure 81: Assembly and connection of Blocks on top of- and next to each other

Developing the Geopolymer playground equipment

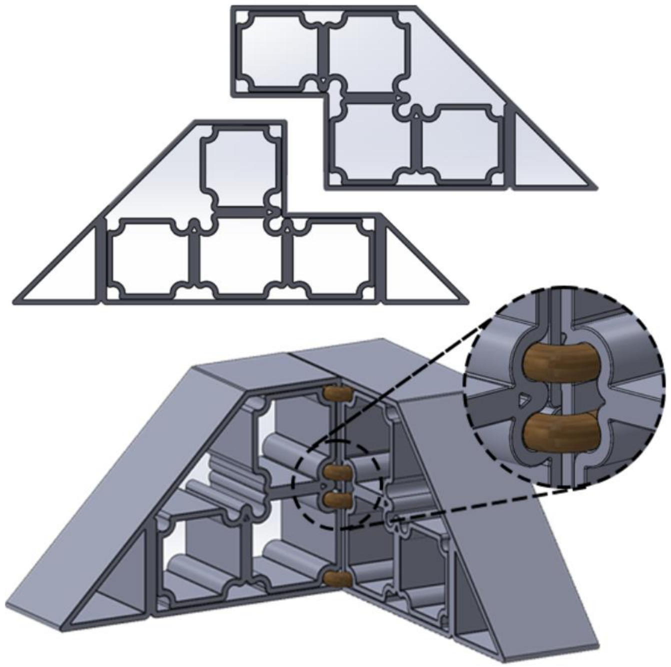


Figure 82: Perpendicular configuration with bended bamboo poles

Figure 83: Bended bamboo through heat bending process [288]

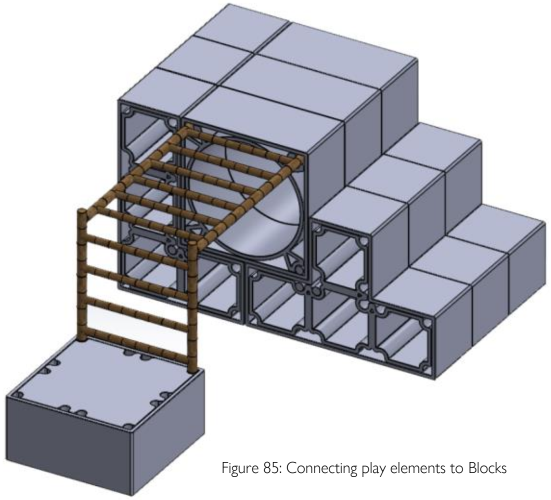


Figure 85: Connecting play elements to Blocks

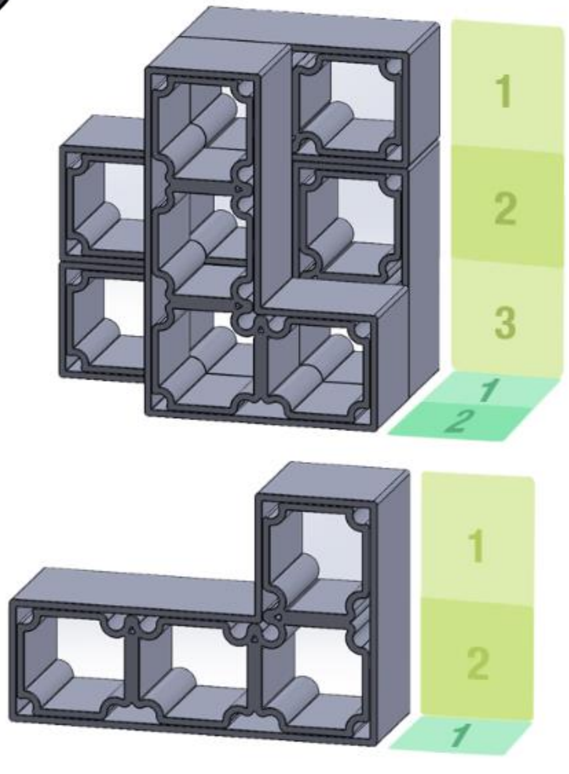


Figure 84: Height construction rule

PE Blocks which offer multiple play functions

As the PE should be able to offer the play functions climbing, swinging & swaying, free running, skating, and BMX I performed studies on these play functions (climbing - Appendix Z, swinging and swaying – Appendix AA, (roller) skating & BMX – Appendix BB), which served as inspiration for an idea sketching session (Appendix CC).

I came up with a range of different configurations of the Blocks and combined these with bamboo and rope elements to add more playability. I also looked at creating structures where children could hang out or 'play in a treehouse/hut', as these were also highly desired play functions and could create a contrast between active and passive play. To conclude on a first set of Geobam PE, to include in a concept sketch, I selected the configurations which would invite children the most to engage in the play functions as concluded on in paragraph 6.2.3 (Figure 86).

Colour of Geobam Play Blocks

Geopolymer can have many different colours due to added pigments (Figure 87) and can even be 'translucent' [292] (Figure 88). Adding colours is important as it makes the PE more interesting and inviting. Also, by adding colours you stay away from the industrial and 'cold' look of the Geopolymer and it will blend in better in a natural environment. Therefore, a study was performed on different colour combinations (Appendix DD). I chose an autumn colour scheme (Figure 89) as the green/ yellow shades blend in well with nature, while orange stands out against the grey of the Geopolymer, creating an interesting and exciting contrast. Orange, yellow and green also come back in the colours of a bamboo pole, creating a uniform colour pallet.

Concept sketch of Geobam Play Blocks playground

The concept sketch on the next page shows different configurations of the Geobam Play Blocks to form PE which offer the aforementioned play functions. Climbing can be done on most of the Blocks, as most of them have a 'stair shape'. Monkeybars and other bamboo play elements are added to several of the Block configurations to add climbing and swinging & swaying playability. A net swing can be hung in between a bamboo pole and a Block to let children swing and sway.

Furthermore, the children can freerun al across the playground by climbing and jumping on and over Blocks and bamboo poles. The different heights and widths of the Block configuration create an exciting parkour for the children to play on. These height differences, together with sloped Blocks and bamboo grind rails can also be used by skaters and children with a BMX to go over or do tricks.

Children can hang out on the blocks, using them as benches. A Square Block with a hole in the middle configurated on top of other blocks can be used as a treehouse or hiding place.

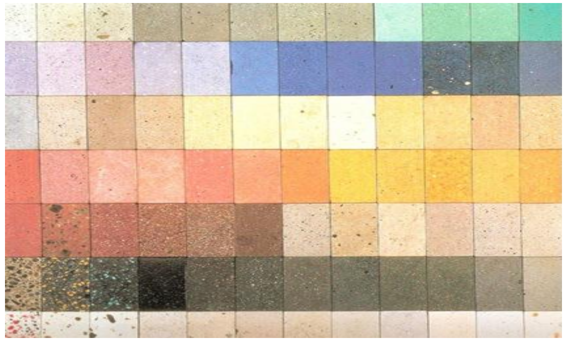


Figure 87: Possibility in colours of concrete pigments [291]

Figure 88: Coloured and translucent concrete blocks [293]

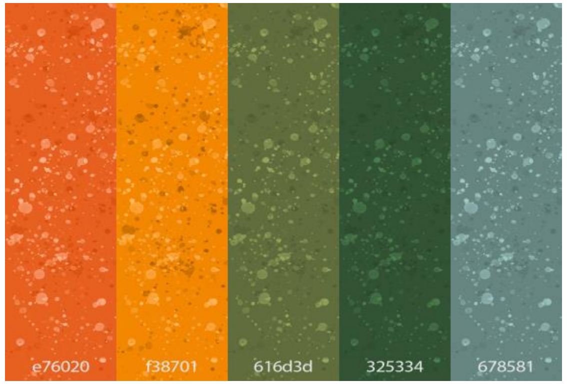


Figure 89: Colour chords of the PE (hex codes included)

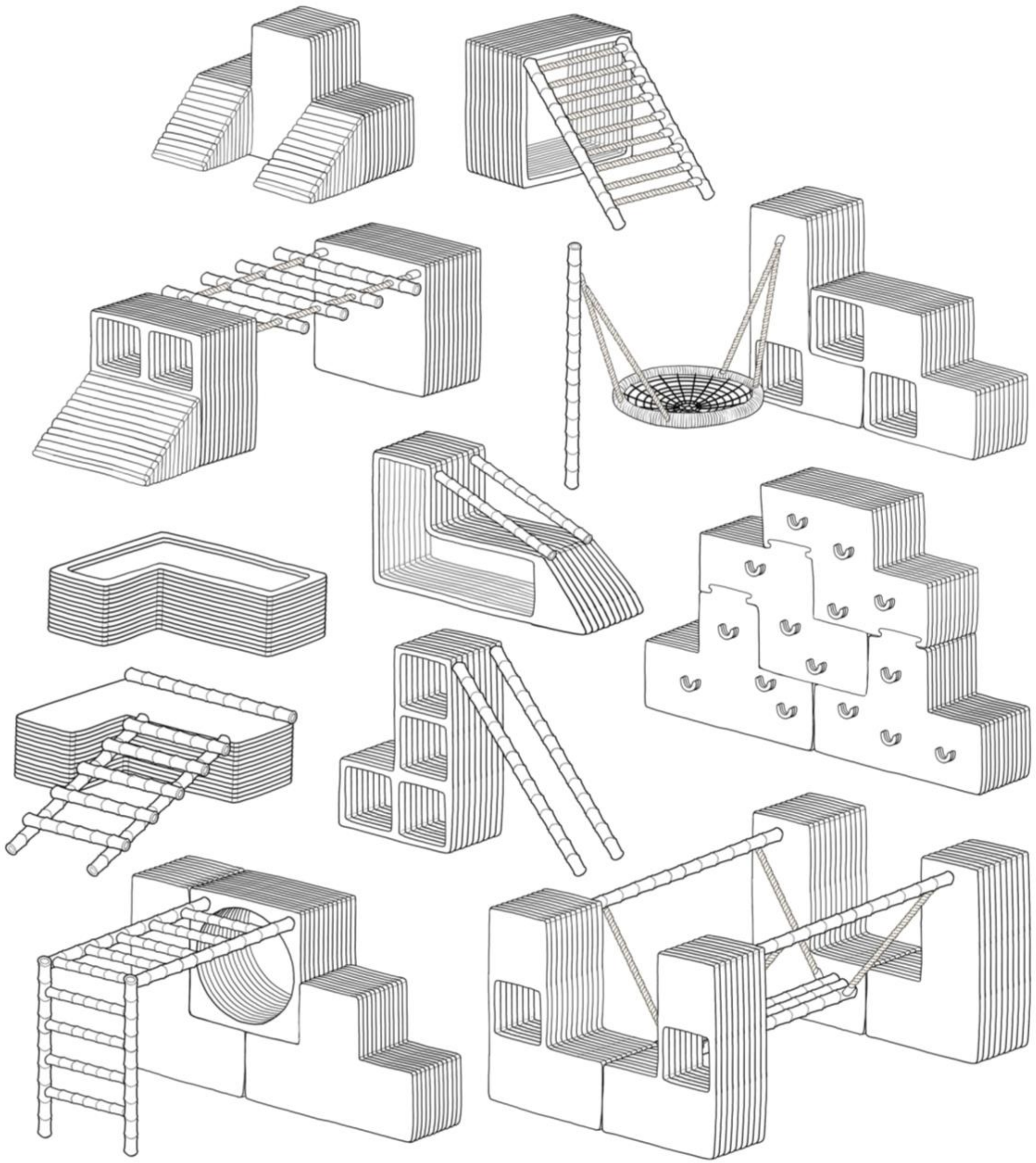


Figure 86: Selection of 3D-printed play modules

Concept drawing of Geobam Play Blocks playground

After examining the concept playground, I concluded that some elements were not really feasible. Bamboo play elements can only be placed on the layered edges of the Blocks with additional connectors, which I want to avoid. Therefore, these will be left out in a new design. I will also eliminate the Blocks that were sloped in the y-direction of printing as such a shape is not possible to print without internal support, which is difficult in 3D Geopolymer printing as discussed in paragraph 4.7.1. Furthermore, as this is a concept sketch, I did not account for the height construction rule, which in an actual playground should be applied.

Three-dimensional scale model of Blocks with 3D-printing

As the Blocks will be used in a modular system, they can be configured almost endlessly to create new and interesting PE. To have a physical representation of what this would look like, I 3D-printed all Blocks in a 1:25 scale (Figure 90). With these 3D-objects I was able to play and configurate them in ways I would not have thought of during the sketching sessions (Appendix EE). Several of these configurations will be used in the final visual and poster of the Geobam Play Blocks concept (Paragraph 7.3). I again chose these configurations based on which would invite children the most to engage in the play functions as concluded on in paragraph 6.2.3.

I printed with a stonefill filament, of which the unique combination of fillers gives the print a speckled surface, creating a realistic stone look.
I used both a light grey and moss green to show that the Geopolymer Blocks will have different colours in the actual playground.

Production of the hollow L-shape Block

The L-shape Block was 'prototyped' and produced at Weber to get an insight into the production process, the printability of the blocks and to conclude on what this concept actually looks liked once it is produced (Figure 91). I chose the L-shape as it showcases the three different heights of the blocks (480mm-960mm-1440mm). The Block consists of 80 printlayers with a witdh of 30 mm and a height of 6 mm. This was chosen as it is the smallest print layer Weber offers, which reduces the overall weight of the Block. The wall-thickness is 60 mm in most places as it consists of the external and internal wall which both have a width of 30 mm. The weight of the Block is +-380 kg.

The protype has been printed in concrete, not Geopolymer, as printing with this material is quite new. Therefore, even though Weber has worked with this material [199] they do not offer this for the printing of just one element, which is understandable. However, as concrete and Geopolymer are almost identical in their material properties such as strength, weight, and look & feel, and their production process (both materials can be 3D-printed in the same machine), I believe it is still of great value to print this prototype.

Printing of the L-shape took 50 minutes, and the price of printing is €794,-, which is mainly based on the amount of material and print duration. Thus, it depends on the volume in collaboration with the print path width, print path height and print speed This price is only a first indication though, and will, with additional optimalisation steps and a bulk price, be decreased [281].

I understand that the price of €794,- only covers production, and additional costs will be made, which will increase the selling price of this product. However, when compared to similar PE I believe that the price-function ratio for the Blocks is favourable. For example, Kompan sells a Robinia wood parkour element (Figure 92) for €1220,-, excl. VAT, which does not include the price of transport and assembly & installation [295]. This Robinia PE has similar dimensions to the L-shape Block (Figure 92) (height 1490 mm – width 620 mm) and can have similar play functions (climbing, sitting, balancing). However, the L-shape Block, on its own, does not need additional assembly steps and does not need to be anchored into the ground, which is the case for the Robinia PE. Also, the Robinia PE has a lifespan of 15 years [296] and cannot be recycled. The L-shape Block on the other hand has a lifespan of 50+ years, can be reused in many other PE and can be recycled at its end-of-life. The price of the Blocks can therefore be spread out over decades of use, with minimal maintenance and repairs due to the chosen material.

Important to note here is that the 3D-print of the prototype was finished after the hand-in deadline of this thesis. Therefore, I was not able to test it and no images of the final printed design can be found here.

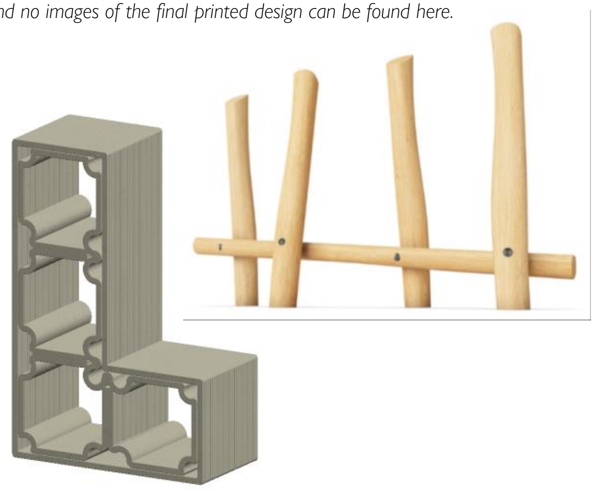


Figure 92: Geobam Play Block L-shape (left) and Robinia parcours element (right) [294]

7. Design

Developing the Geopolymer playground equipment

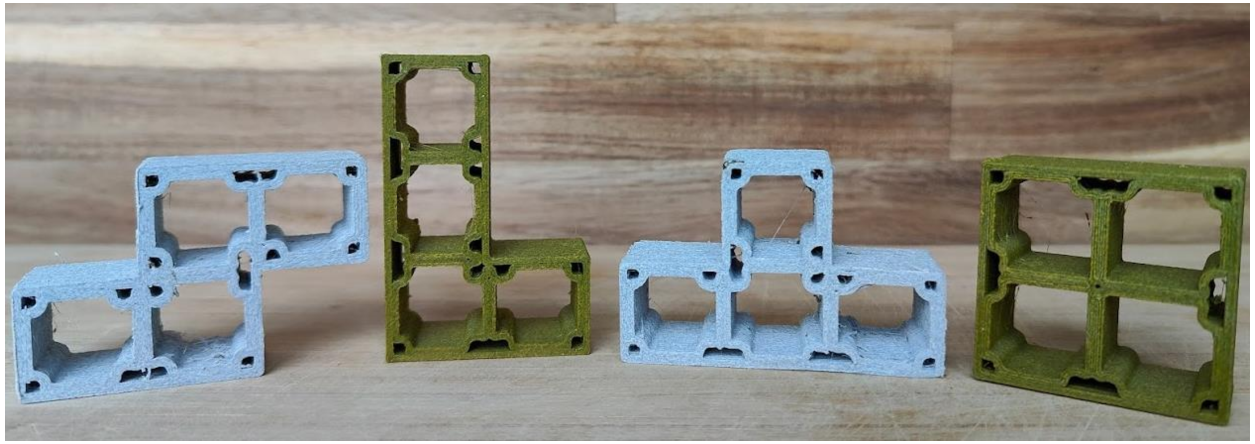


Figure 90: 3D-printed configurations of scale model Geobam Play Blocks

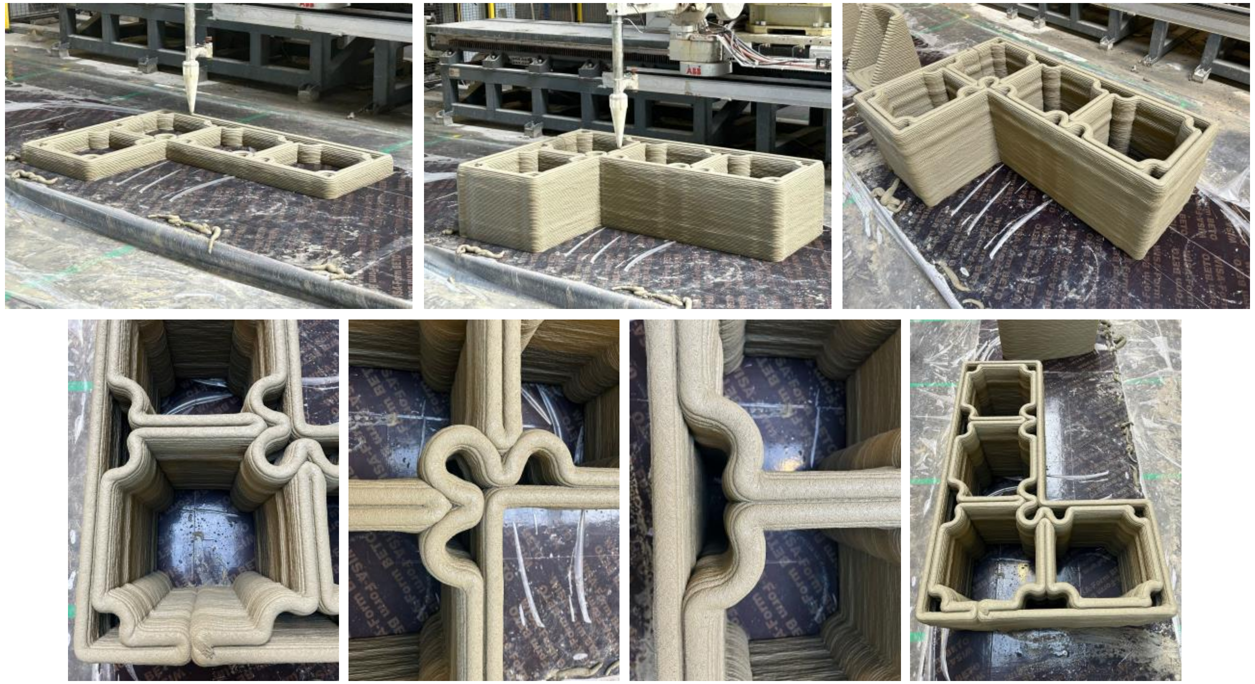


Figure 91: 3D-printing of Geobam L-shape Play Block prototype at Weber

Business model (PSS) and supply chain

7.2 Business model and supply chain

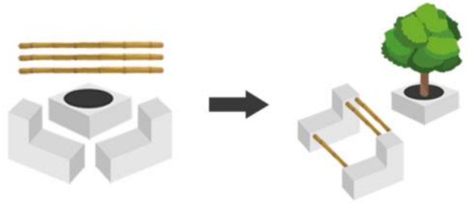
The Geobam Play Blocks will be offered to schools and municipalities by means of a product-service system (PSS) which is use oriented. More specifically, this system will focus on product leasing and, in a way, also product pooling as multiple users, children, can make use of the same product [297]. Therefore, the Geobam developer will have ownership of all the Blocks. A big difference between these two customers is that a school only wants and leases one playground (or two/three depending on the size of their schoolyard), while the municipality wants and leases several all over the municipality. Therefore, the way the PSS works is slightly different for them. By means of an infographic I want to explain how the PSS and the overall supply chain works.

Phase 1 | Production and storage

The Geopolymer, used as the Blocks material, will be made from 'waste' material (geopolymer) and recycled aggregates coming from a Dutch recycling plant (1). These materials are turned into 3D-printable Geopolymer, and send (2) to the printing factory (3), where they will 3D-print a collection of Geobam Play Blocks. These Blocks, together with bamboo poles coming from a Dutch bamboo farmer (4), are brought to the Geobam warehouse (5) where they are stored (6).

Phase 2 | Design of the playground (equipment)

When a school (7) or municipality (8) is interested in leasing a Geobam Play Blocks playground, the Geobam developer/owner (9) will first discuss their needs and wants, and more importantly those of the children that will be playing on it. Depending on their wishes the developer can offer existing Block packages:



Or design new configurations of Blocks and bamboo. They will also, with this pre-determined collection of Geobam PE design the playground itself.

Designing the new configurations and playground could be done with a specially developed 3D-modelling program, in which all individual Blocks can be configurated easily. This could also be done together with the client to create the feeling of collaboration, where the client feels a more personal connection with the playground as they designed it themselves, touching on the principles of emotional durability and product attachment, as discussed in paragraph 3.4.

7. Design

Business model (PSS) and supply chain

Phase 3 | Assembly and construction

When the design has been made, Block packages will be sent to the desired location (10) and the playground will be constructed by assembling the Blocks and bamboo (11).

Phase 4 | Maintenance and repair

Besides leasing the Blocks, schools and municipalities are also offered a maintenance and repair service, which include replacing of screws and bamboo (11) and the repair of the Geopolymer Blocks should a piece break off (which is very rare in this use case).

An external party could be appointed by the municipality, as they often have their own maintenance teams, but only in agreement with the Geobam developer (as their standards might be different, making the Blocks unsuitable to be reused).

Therefore, the PSS also includes a workshop in which municipal maintenance teams are thought how to maintain and repair the Blocks, and parents, teachers and concierges are thought how to take care of simpler and smaller maintenance tasks (12).

Giving the teachers and concierges the partial responsibility of maintenance and repairs will increase the product-user bond, as they have to take care of their own product and will decrease the amount of times the developer has to show up with a team which is both costly, time consuming and results in additional transport.

Phase 5 | Exchanging Blocks

Customers have the possibility to replace, exchange, add or remove Blocks, but only after an X number of years. This way, the playground will stay interesting for the children and can change according to the shifting preferences of its users. To decrease the amount of labour and the influx of new Blocks, the developer will first see if small changes can be made, such as adding new bamboo play elements (11) or exchanging Blocks within the same playground (13).

To municipalities it is encouraged to lease several playgrounds worth of Geobam Play Blocks, as these can be endlessly exchanged between these playgrounds, found in neighbourhoods (14), parks (15) and city squares (16), within their municipality. Thus, a system is created in which new playgrounds can be developed within the municipality without the need for new PE (17).

7. Design

Business model (PSS) and supply chain

Phase 6 | Reuse, repurpose or recycle

At the end of a leasing contract the customer can decide to extend it. However, should this not be the case, the Blocks will be examined and according to their condition the following things can happen:

If they are suitable for reuse:

- They will be used in a playground from another school or municipality (18).
- They will be taken back to the Geobam warehouse, where they can be reused later (19).

If they are not suitable for reuse:

- They will be taken back to the Geobam warehouse and repaired to be reused later (19).
- They are repurposed in other projects, such as a planter (20).
- They are brought to the recycling facility (21).

Geobam Play Blocks final design proposal

7.3 Geobam Play Blocks final design proposal

My research and design process have led to the final design proposal, which I want to discuss here. The visual on the right displays the Geobam Play Blocks in an urban setting, which could be a neighbourhood in Leiden or a city square in Rotterdam. Here you can see a playground build-up of several Geobam Play Block configurations, which make for exciting playground equipment that offer the play functions climbing, swinging & swaying, free running, skating and more. I will go through the different parts of the playground, which I have given names such as 'Adventure Mountain' or 'Jungle Parkour'. In the left bottom I also added the 'comprehensive playground directions' (CPD) to show the main type of play (functions) that are offered by this playground equipment. Of course, these are just a handful of Block configurations. The main premise of the Geobam Play Blocks of course is that they can be configurated in any way the client wants or needs and can be played with however a child desires.

Even though I concluded on a colour scheme which includes yellow and orange, I made the choice to only make the Blocks grey and green in the visuals because I did not want to put the focus too much on these colours and more on the equipment themselves.

The 3D renders were not made by me, but by G. van Nifterik (Design and presentation specialist at van Ee Speel). I did make the 3D models of all the Geobam Play Blocks, bamboo elements and their configurations, and added all the additional elements such as the children, numbers, etc.

Adventure Mountain

The first playground equipment in the playground is the 'Adventure Mountain'. It consists of several T-shaped, L-shaped and Cube-shaped Blocks to form a large climbing structure or "mountain'. The Cube-shaped Blocks with an opening (1) allow children to climb through them, almost like a cave. This element touches upon the CPD Treetop Retreat and Hideaway Hunt.

The ribs within the Blocks allow children to climb on top of the structure (2). Once at the top they can hang out on this platform (Treetop Retreat) or jump off on the wood chip underground, which will soften their landing.

The bamboo monkey bars (3) are connected to the mountain and a horizontally placed Cube-shaped Block on the ground. These monkey bars can be used for climbing, swinging & swaying and free running (Acrobatic Adventure).

The stair shape of the mountain (left side) can be used to climb on or hang out. The difference in height of the Blocks allows children to climb, run and jump on and of them (4) (Acrobatic Adventure).

7. Design

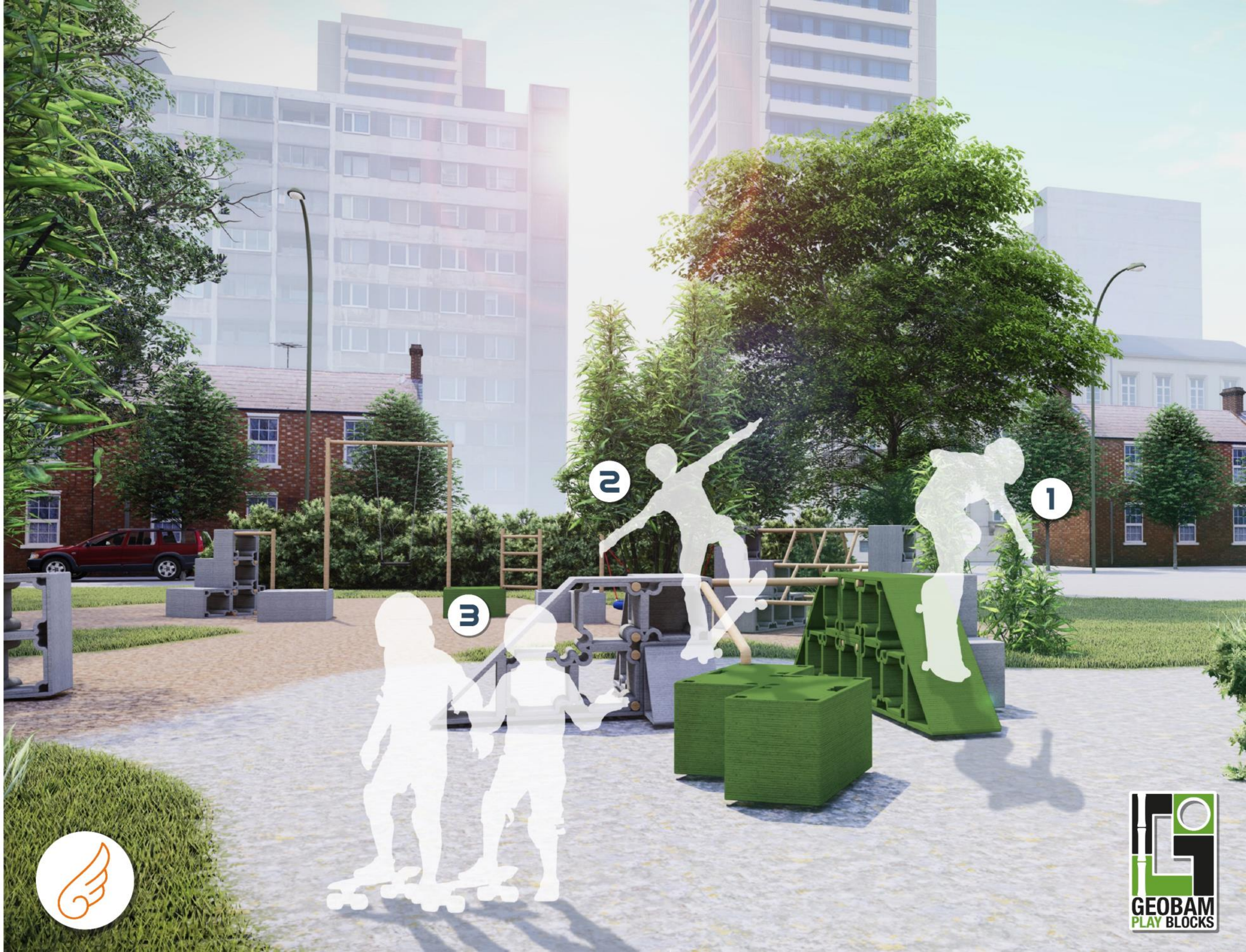
Geobam Play Blocks final design proposal

The Urban Wave

The Urban Wave is a configuration of slanted Blocks which form equipment that can be used for (roller) skating, focussing on the CPD Rapid Rush. The slanted Z-shaped Blocks can be used to ride off with a skateboard or with roller-skates (1).

Bamboo poles, secured in-between a vertically and horizontally placed Block, can be used as a grind rail (2), to skate underneath or as a handle for inexperienced skaters.

The Urban Wave is placed on a hard service, such as Geopolymer or bricks, which allows children to skate around this playground equipment (3).



7. Design

Geobam Play Blocks final design proposal

Jungle Parkour

By connecting several Blocks with bamboo you can create an obstacle course with different play functions where children can climb, jump and run from one end to the other (Rapid Rush and Acrobatic Adventure). The different Blocks can also be used to hide behind during a game of hide-and-seek (Hideaway Hunt).

A bamboo frame can be placed in between two vertically placed Blocks to create a swing (1) or a net swing can be secured between a bamboo pole and an L-shaped Block (2). This way you offer the play function 'swinging & swaying' to different age groups with different heights. A bamboo pole can also be used as a tumble bar (3).

Several bamboo poles can be connected together and in between L-shaped and T-shaped Blocks to create an interesting and challenging climbing structure (5).

Open spaces should be created for children to run around or play tag and soccer (4) (Rapid Rush). Openings in between Blocks can be used as goals for children to shoot a ball trough.

7. Design

Geobam Play Blocks final design proposal

Balance Bridge and Repurpose

The Balance Bridge is playground equipment which can be used to walk over and keeping your balance (1) (Acrobatic Adventure). Bamboo poles are placed in between two Cube-shaped Blocks to form a bridge.

The Blocks can also be repurposed in a playground. For example, the Blocks can be placed vertically in a rectangle to create a pit which can be filled with sand to create a sandbox (2) (Hideaway Hunt and Treetop Retreat). Bamboo poles are inserted into the vertically placed Blocks and a canvas can be hung-up in between these poles to create shade for the children playing in the sandbox.

A Block can also be used as a planter (3). Grassy plants or flowers can be planted here for children to take care of.

Providing an answer to the research question

To find an answer to the research question and sub-questions I conducted research on the existing approach and methods of product and playground equipment developers, as well as uncover how the circular product design principles could be effectively applied in playground equipment design. Furthermore, the conclusions from a literature study on different relevant materials and interviews with experts substantiated my choice for an appropriate playground equipment material which fits in a CE. Lastly, by conducting academic research on desired play functions and increased physical activity and wellbeing in playgrounds and finding possible parallels with my own conducted design session, I was able to conclude on design considerations which increase outdoor play.

Therefore, in this chapter I would like to conclude on my research by providing answers to the research question and sub-questions as provided in chapter 2 Method.

8.1 Answer sub-question 1

How have circular design principles already been implemented in product and playground equipment design, and how can design considerations increase its effectiveness?

Refuse, rethink and reduce (R3A) have been effectively implemented in PE by means of 'smart solutions' which offer the same functionality and playability while decreasing the number of parts and materials.

Designing PE by implementing smart-solutions, thus eliminating redundant elements, with modules that can fulfil multiple play functions and are made from a mono-material (which allows for form freedom) can further increase the effectiveness of these circular principles, as the number of materials, parts and equipment is reduced while providing the same functionality and playability.

Durability is implemented by making PE from 'durable' materials, where durability is related to enduring changing conditions over time such as wear and tear. By making the PE modular and adaptable, where the customer is allowed to choose their own modules and configurate them to fulfil their needs, the design is also more durable, as it can not only endure physical conditions, but also the changing demand of its users throughout its multiple lifecycles.

Reuse of PE is implemented to some degree, as they are sometimes reused on site or by retrieving them from playground depots. However, many complications arise in doing this. Designing the PE to be applicable in a PSS, by designing modular and interchangeable modules which are easy to (dis-)assemble can increase the reusability of the PE in an effective system.

Effective repair and maintenance is embedded in part of the existing PE, as these are made from materials which can easily be repaired due to their material properties or minimal need for maintenance. To further make repairs and maintenance efficient the connection system of the PE should be designed to simplify (dis-)assembly which allows problem areas to be reached more easily. Furthermore, a PSS encourages proper maintenance and repairs which allows the PE to be reused in this system, which could also be referred to as refurbishing.

Repurpose is implemented in playground design by reusing 'waste' objects such as concrete tubes. However, repurpose can also be implemented by designing the PE modules in such a way that they provide multiple (play) functions and in this way can be repurposed as another piece of PE or even a different product, for example a planter.

Some PE is made from recycled materials, such as plastic. However, recycling of the PE at its end-of-life is not often expressed by PE developers. To design PE which can be efficiently recycled, a mono-material should be chosen which allows for this. Furthermore, the PE should be designed with an easy to (dis-) assemble connection system, which allows for more effective separation of the materials. Furthermore, by making the PE from a material which comes from a waste stream, material reversibility is achieved.

8.2 Answer sub-question 2

How can material choice contribute to the effective implementation of the circular product design principles?

By choosing a material which allows for a lot of form freedom, modular PE modules can be produced which can fulfil multiple play functions.

The material should also be durable and easy to repair and maintain, as this allows it to have a lifespan of several decades, which makes it appropriate to use in a PSS, where the PE is reused multiple times by many different users and has to endure different conditions such as weather, wear and tear, transport, etc.

Lastly, the material must allow for efficient recycling at the end of its life. Here, it is important to consider how much of the 'waste' material can be recovered during recycling to be used in a new product (low % of virgin material needs to be added) and if the recycling process does not require much energy and result in significant carbon emissions.

To fulfil most of these considerations, the PE as proposed in this project will be made from 3D-printed Geopolymer with the addition of bamboo.

8.3 Answer sub-question 3

How can design considerations, regarding PE, contribute to increased outdoor play, physical activity and wellbeing among children?

PE should be designed to facilitate many types of play and offer several play functions which allows children to play in their own way. By designing PE which facilitates and encourages children to climb, swing & sway and free run, and engage in adventurous and 'risky' play, such as skating, the physical activity and wellbeing of children can be increased as well as encourage them to play outside more.

8.4 Answer to the research question

How can circular product design principles be effectively applied to the development of sustainable playground equipment, while the design also improves children's engagement, physical activity and well-being?

The circular product design principles can be effectively applied to the development of sustainable playground equipment by carefully considering and utilizing the accommodating design considerations. These design considerations are the following (a more elaborate explanation on each of the design considerations can be found in paragraph 6.3):

- Create an interchangeable and customizable system with components that are easy to (dis-)assemble (PSS with modular play modules)
- Design with a mono-material
- Design with a material which comes from a waste stream
- Design with a material which allows for form freedom
- Eliminate redundant elements
- Design PE modules which can fulfil multiple play functions
- Design a connection system which allows for easy (dis-)assembly and consists of a minimal number of parts and different materials
- Design with a material which is resistant to wear and tear and external conditions (cold, heat, moist, UV radiation, etc.)
- Design for effective and minimal repairs and maintenance
- Design with materials which can efficiently be recycled

These design considerations should be embedded in PE design which facilitates the play functions climbing, swinging & swaying and free running, with a focus on adventurous or 'risky' play, such as skating, as these play functions improve children's engagement, physical activity and wellbeing.

9. Discussion

Reflection on results and conclusion

Overall, I stand behind the claims which are expressed in Chapter 8 Conclusion. The provided design considerations will, in theory, clear the path and provide benefits to apply the circular principles to PE. This thesis furthermore moves the field of playground equipment design forward, as research on circularity within this field is rarely discussed in academic literature.

However, the research approach in this thesis has several limitations which was due to my planning and prioritization as a result of the scope I constructed for this project. Furthermore, during the project I did certain things and made decisions which, in hindsight, could have been done in a more effective way. I will discuss these limitations and shortcomings in this paragraph which will help academic researchers and the playground (equipment) design field to generate new approaches without facing the same challenges.

Geopolymer printing in a modular system

Based on academic literature and expert interviews, I concluded that printing of Geopolymer was the preferred method to produce the PE. This is because printing decreases the amount of Geopolymer needed to make an object and eliminates the need for moulds.

However, the environmental impact, such as energy use and carbon emissions, of producing such PE by means of casting or printing can only be substantially determined when an additional study and calculations are performed. A limited number of studies on the comparison of the environmental impact of casting or printing of Geopolymer has been conducted, of which the results differ from case studies in the field of Geopolymer product production.

Furthermore, when considering a production process for a product which will be produced in large quantities, which is often the case in modular products, casting is often the more straight forward and preferred option, as it decreases lead times.

Therefore, in order to formulate a substantiated conclusion on which production process creates less environmental impact and is a more effective process in producing the PE modules, additional research and calculations should be carried out.

Conclusion on play functions

The conclusions on play functions are derived on a comparatively small group of children (131 in total) which was needed to set boundaries within the timeframe of this project. Therefore, the results and conclusions on the preferred play functions cannot be adopted as representative for the entire user group. Design sessions with children from different schools, cities or countries could potentially result in very different results.

Although, it was interesting to see that there is a parallel between the results of the design sessions, even among different age groups, and the conclusions from the literature study, indicating that the session that I constructed for this thesis provokes children to respond in a valuable manner. The success of the sessions is partly based on the relevance of the guidebook 'Your Turn for the Teacher' by Klapwijk et al. [26].

Furthermore, I made the decision to include the specific play functions climbing and swinging & swaying, among several others, as these, according to the literature study and design sessions, would result in more physical activity among children and encourage them to play outside more. However, as the purpose of the circular PE is to be reused throughout multiple lifetimes, this could work counterproductive as preferences and play trends change. Even though this has been accounted for by creating a modular system with many different play modules which include several play functions, the reality of children playing with these as intended can differ.

Therefore, to conclude on the preferred play functions among children additional design sessions should be carried out among several schools and cities.

User testing of the playground equipment

Within my planning I did not allocate time for user testing of a prototype. This was because there was no budget to print multiple PE modules, which are needed to configurate a playable object. Therefore, conclusions on the success of the design of the PE regarding playability and safety were only derived from secondary sources, such as looking at existing PE and safety regulations as expressed in the NEN-EN documents. To develop the design further in terms of playability and safety several modules should be 3D-printed and tested with a wide range of children from different age groups.

Connection system

I decided to look at the actual design of the connection system at the end of the project, mainly because I just had a lot of other things to do. This left me with limited time to work on this and therefore did not result in the best possible solution. Even though I tried to optimize it as much as possible, I still want to figure out how to create a mono-material connection system made using 3D-printing which enables the Blocks to be configurated in several directions.

Therefore, I should have prioritized the design of the connection system more as it is a very important factor in the successful implementation of the circular design principles, as a well-designed connection system can create benefits for maintenance, repair, reuse and recycle.

10. Recommendations

Recommendations to further develop circular and sustainable playground equipment

The PE design, as proposed in this thesis, encourages researchers and the field of playground design to look at C&S in PE design in new and interesting ways, which have not been developed yet. Therefore, I would recommend to develop the proposed PE further.

However, even though this thesis lays the foundation for such development, I recommend to conduct additional R&D to substantiate several claims that I made, as well as make the proposed PE into a marketable product. Therefore, in this paragraph I want to discuss my recommendations.

Playground equipment PSS pilot

As part of the overall design direction, I recommend to offer the modular PE by means of a product-service system (paragraph 7.2).

Such a business model can facilitate many circular benefits but is quite new in the field of playgrounds. Furthermore, no academic research or pilots have been conducted on a PE PSS and therefore its effectiveness can only be described in a theoretical sense.

Therefore, in order to conclude on the effectiveness of such a business model I recommend to set-up a pilot with several schools and neighbourhoods. These are offered a collection of pre-determined PE modules which will be constructed into their preferred playground equipment.

As the need-cycle for new PE is 7 years, which is too much time for a pilot, part of the original PE in one location will be switched with those from another location 6 months after the start of the pilot.

The following can be learned from such a pilot:

1. The perception, doubts and concerns of the leasers
2. The children's (users) view on their playground changing
3. Complications which might arise during dis-assembly of the Blocks
4. Complications which might arise during and after transport
5. Complications which might arise during re-assembly
6. The viability of a PSS in terms of costs. For example, can the price of leasing cover the (dis-)assembly and transport costs?

These results will further substantiate the effectiveness of a PSS in the field of playgrounds and will help to further develop circular PE.

Casting or printing of Geopolymer playground equipment

As I already explained in paragraph 9 Discussion, additional research on the production process of the Geopolymer PE is needed in order to choose the one which has the lowest environmental impact.

As academical research on the comparison of casting or printing of Geopolymer is limited I recommend to perform additional research on just this topic to not only complement the research as performed in this thesis, but also to accommodate in the development of this new material.

Furthermore, in order to make substantiated claims on the preference for casting or printing I recommend to conduct additional research on the production of the Geobam Play Blocks by means of both printing and casting.

Such a study should be performed in collaboration with a company who specializes in both production processes in order to eliminate as many variables as possible. Such a company also has a lot of expertise and knowledge on this topic and can conclude on the environmental impact of both production processes.

Preference of play functions

As I discussed in paragraph 9 Discussion, my choice for certain play functions is derived from the conclusions of the design sessions, which are based on a comparatively small group of children. These results are therefore not representative for the entire user group and should not be adopted as such.

To make more substantiated claims on the preferred play functions of children I recommend to conduct several additional design sessions with groups of children from different age groups and cities/ villages to conclude on a possible consensus between these varying groups.

To conduct such relevant and insightful design sessions, I advise to make use of the 'Guidebook Your Turn for the Teacher' by Klapwijk et al. [26], if it is a researchers or designers' intention to do research on children's perception on or wishes regarding a certain topic. This guidebook was very helpful in setting up a relevant design session to retrieve valuable results on the preferences for certain play functions by children.

One point of attention would be to make sure that the developed exercises are understandable and doable for the age group that is going to be involved in a design session. For example, 'Exercise 2 Empathic design challenge' (Appendix B, page 93-94) was not always understood by both the younger (age 6-7) and older (age 8-11) children, as they had a difficulty to think about a future scenario without already being in the solution space.

Recommendations to further develop circular and sustainable playground equipment

Improve children's wellbeing | Inclusivity

Playgrounds are an important place for children to exercise and socialize. Therefore, it is important to make the playgrounds inclusive which allows children with a physical or mental disability to play on the playground together with other children without being hindered in any way. This improves the wellbeing of all children as they feel included and learn to play together.

Due to prioritization, I performed only limited research on this topic and did not include any of the proposed solutions in my PE design. However, as it is an important step to create a valuable play experience for all children, which touches upon the social aspect of sustainable design, such design considerations should be implemented in playground design from here on forward.

Several playground equipment developers already design inclusive playgrounds, but their solutions have been criticized by academics such as Brown et al. [255] (A scoping Review of Evidence-Informed Recommendations for Designing Inclusive Playgrounds), Mor [256] (Inclusive Playground Design: Promoting Social Inclusion for Children with Disabilities) and van Melik & Althuizen [257] (Inclusive Play Policies: Disabled Children And Their Access To Dutch Playgrounds) who all emphasize the importance of offering opportunities for children to play together without shame or barriers, as opposed to offering expensive adjusted play equipment.

However, additional research on inclusive playground design is needed to create a better understanding on this topic in the field of playgrounds. To do this, I recommend to build onto the research from Brown et al. [255] and Mor [256], and to conduct qualitative interviews with children with a disability and their families to uncover their needs and preferences. Such interviews can be of great value as misconceptions on inclusive play can be resolved when the user is actively involved in the decision making [257].

Additionally, when such an inclusive playground is developed, I recommend to have it thoroughly tested by the 'Speeltuinbende', which is an initiative from the foundation 'Stichting het gehandicapte kind' where a group of children with and without a mental or physical handicap test playgrounds on its inclusivity [258]. Receiving feedback from this test-group is of great value for the development of inclusive PE.

Improve children's wellbeing | Climate-smart design

As the changing climate might dictate the availability to play outside, designing PE with climate-smart solutions is of importance to the wellbeing of children. Such solutions can protect children against the sun, which decreases the negative impact on their health and increases their playtime as the heat, which also makes some equipment unplayable, does not affect them as much.

Again, due to prioritization I did not conduct additional research on this topic. However, as climate issues will become more prominent in the future, making substantiated design decisions accordingly is important to improve children's wellbeing.

Academic research on this topic has been conducted by Pfautsch et al. [271] (Outdoor playgrounds and climate change: Importance of surface materials and shade to extend play time and prevent burn injuries) and Pfautsch & Wujeska-Klause [272] (Guide to Climate-Smart Playgrounds: Research Findings and Application) but the quantity of such research is still quite limited. I therefore recommend to build upon the aforementioned research which can help PE developers to design playgrounds which allow children to keep enjoying playing outside without having to worry about their physical wellbeing.

Specifically, attention should be paid to choosing materials which cannot cause burns when heated by the sun, which is the case for some types of metal. I conducted research on the material behaviour of Geopolymer regarding its tendency to heat up by the sun, which should not be able to harm children. However, to conclude on the behaviour of this material in PE I recommend to study this in a real-life scenario. A Geopolymer PE prototype should be developed and placed in the sun or a similar fabricated environment, where its outside temperature will be measured.

Furthermore, creating shade is important to enable children to play longer and without barriers. I recommend to conduct research on solutions which can protect children from the sun but are also in line with the circular design considerations which I concluded on. For example, large canvasses can be hung up on the bamboo poles, which are made from recycled fabric, are durable and can be easily repaired which allows them to be reused several times and can be recycled at its end-of-life. Additional design sessions can help with finding the right size and shape, as well as a system to connect such a canvas to the bamboo poles which allows for easy (dis-)assembly.

Recommendations to further develop circular and sustainable playground equipment

Effective repair and maintenance

To make repairs and maintenance more effective and efficient I already implemented several design considerations into the design of the proposed PE, such as the material choice and the method of (dis-)assembly of Geobam Play Blocks.

However, as was expressed by van Ee, when applying a PSS, performing sufficient safety checks (which precede repairs and maintenance) by the developer becomes difficult, and this responsibility should be transferred to an additional party which ensures such checks are carried out in a sufficient and timely manner.

This additional party can consist of several stakeholders, such as teachers, concierges or parents at a school or parents and social workplaces, such as DZB Leiden, in neighbourhoods. All of these stakeholders have been assigned such responsibilities by several PE developers, but no clear conclusion can be drawn on which is most effective, and no guide exists on how to train parents or teachers to carry out such tasks. Therefore, I recommend to conduct research on this topic by performing a pilot in which such stakeholders take part in the repair and maintenance procedures. By uncovering complications during these procedures and discussing preferences a guide can be constructed to educate these stakeholders on how to perform such repairs and maintenance themselves in an effective and efficient manner. Transferring this responsibility partly allows a PSS business model to be implemented in the field of playgrounds and also enables repairs and maintenance to be carried out in a timely manner [108], so that children are not hindered in their play activities.

Co-creation with municipalities

As I discussed in paragraph 3.5.2, 3.6.1 and 5.1 municipalities have a big influence on new developments within the field of playgrounds and PE. Even though they are working on circular developments in this domain, several of their choices and regulations still hinder circular innovations which is already discussed by Oost-Mulder & Van Weert in their 'Handreiking voor een circulaire werkwijze bij de inrichting van speelruimte' [4].

One of these developments is the Leidse ladder, which guidelines ensure that projects within the municipality, playgrounds included, result in less released CO_2 equivalent and a lower MKI. However, some guidelines in this model are not always in the best interest of circularity and sustainability. For example, the LL highly rewards the use of biobased materials in the 'material use' aspect, but the environmental impact isn't always guaranteed to be positive [12].

Therefore, I believe it to be important that such models should be re-examined, and I therefore propose that a new guide or model should be developed which is accessible to all Dutch municipalities. Interviews and discussions with both academics, companies and relevant departments within the Dutch municipalities should be conducted to bundle their expertise and knowledge and create a common understanding of how to develop circular and sustainable products and projects, of which playgrounds and PE is one direction. The research in this thesis, together with models like the Leidse Ladder and the '5 strategies for circular playground design' could serve as the basis of this new model.

Additionally, this study should focus on the current safety regulations and uncover a way to create a new understanding of safety within playgrounds which opens up possibilities to make them more challenging and exciting for children, needed to encourage them to play outside more.

Improve reuse possibilities within playground depots

I made it the objective of the design part of this project to develop new PE. Therefore, I rejected the approach of reusing discarded PE from playground depots, while it additionally created several limitations and obstacles.

However, reusing discarded PE could be an effective way to create circular playgrounds as 'old' PE can be re-introduced into the loop and last another round.

Therefore, I recommend to conduct additional research on the effective reuse of PE from playground depots, as they have a lot of equipment laying around which is now unused. Interviews should be conducted with municipalities, PE developers and depot managers to uncover their concerns and create a common understanding of how such a system can work. Paragraph 3.7.1 of this thesis already discusses the concerns from the playground depots and could therefore serve as a starting point for this study.

Strength and durability bamboo and connection system

As I did not allocate time for testing some of my design choices, such as the width of the bamboo poles and the connection system, I cannot conclude on the PEs ability to hold playing children or to keep the Geopolymer Blocks together. Therefore, to make a substantiated claim on the appropriateness of this connection system I recommend to perform strength tests on different widths of bamboo poles and a connected Block configuration. With this knowledge it becomes clear if such a connection system would work and what needs to be changed or improved, such as the width of the bamboo, the number of screws and the configuration of the screw holes.

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Project brief as approved at the start of the project

Personal Project Brief - IDE Master Graduation

TU Delft

Designing sustainable playground equipment

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 03 - 07 - 2023 31 - 01 - 2024 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Van Ee Speel is a Netherlands-based company dedicated to transforming outdoor spaces into multifunctional play and exercise landscapes, such as schoolyards, neighborhood playgrounds and recreational fields. They create outdoor spaces that are attractive for everyone to be in, move in, meet and enjoy. In doing so, they take into account the needs of the users, environment of the location and the social context. Specifically, they perform the following functions: Assisting with design and participation, supply and placement of equipment, and inspections and maintenance of both playground equipment and surfaces.

When designing playground equipment, little or no consideration is often given to separating the materials at the end of their useful life, sustainability and circularity. Moreover, plastic playground equipment creates large amounts of microplastics (Koutnik et al., 2022), which is both a problem for nature, and the health of children playing. In addition, building and installing these playgrounds takes a lot of time and money: The materials are expensive, a lot of transportation is needed, and technical people are scarce and are becoming more expensive, which can no longer be solved with low educated people.

This is a big obstacle for van Ee, because more and more municipalities are setting circular goals and getting started with sustainable procurement, especially when it comes to the construction and demolition sector: It is responsible for 50% of the total Dutch raw material use, 40% of the total energy consumption and 40% of all waste. This makes the chain responsible for 35% of all CO2 emissions. The objective from the municipality of Leiden, for example, is therefore to call for municipal building projects to be 100% circular from 2023 (Gemeente Leiden, 2023). These projects include the transformation of outdoor spaces into playgrounds.

As a playground designer and builder, van Ee Speel has an interest in keeping in touch with their clients regarding sustainable purchasing, flexible reuse and limiting labour costs. By developing new playground equipment and coming up with new material/product combinations, they can realize circular playgrounds in the future. A prerequisite in today's world.

Gemeente Leiden. (2023). Programmabegroting 2023. programmabegroting.leiden.nl. Geraadpleegd op 3 mei 2023, van https://programmabegroting.leiden.nl/beleidsbegroting/programmaplan/economie

Koutnik, V. S., Leonard, J., Rassi, L. A. E., Choy, M. M., Brar, J., Glasman, J. B., Cowger, W., & Mohanty, S. K. (2022). Children's playgrounds contain more microplastics than other areas in urban parks. Science of The Total Environment, 854, 158866. https://doi.org/10.1016/j.scitotenv.2022.158866

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Project brief as approved at the start of the project

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TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The biggest problems of "van Ee Speel" are the following:

1. Little or no consideration is given to the separation of the materials from the playground equipment at the end of its useful life (sustainability and circularity), while municipalities have high requirements regarding sustainability.

2. Building and installing this playground equipment takes a lot of time and money: The materials are expensive, a lot of transportation is needed and technical people are scarce and becoming more expensive.

One solution that Van Ee has already suggested is reusing parts from other sectors. For example, a playground in Rotterdam is made from the blades of dated wind turbines called Wikado. However, because these blades were not designed for this purpose, later complications have occurred, calling into question the safety of this type of solution (Medici et al., 2020).

To meet the requirements of municipalities and to save costs, more durable playground equipment which can be built and installed more efficiently should be considered. However, playground equipment must still meet a lot of requirements, such as safety, playability and presence in the streetscape.

Medici, P., Van Den Dobbelsteen, A., & Peck, D. (2020). Safety and Health Concerns for the Users of a Playground, Built with Reused Rotor Blades from a Dismantled Wind Turbine. Sustainability, 12(9), 3626. https://doi.org/10.3390/su12093626

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

I will design a line of playground equipment that will be made from a sustainable material, be more recyclable, more efficient to transport and install, while maintaining playability and enriching the streetscape.

The solution will primarily be a product (or several products). The actual end result of my thesis project will be a concept, where parts of the product will be presented in the form of a prototype.

Project brief as approved at the start of the project

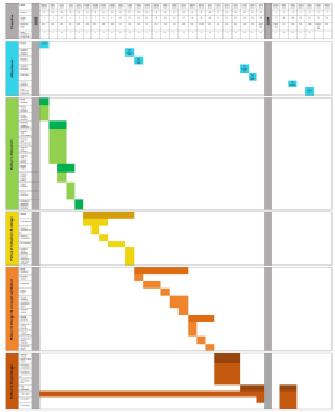
Personal Project Brief - IDE Master Graduation

TU Delft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 3 - 7 - 2023 | 31 - 1 - 2024 end date



In addition to graduating, I want to work part-time at a design firm. I made this choice because I would like to gain more work experience. In order to still make sure that I can graduate in January, I want to start my graduation project in July, so that I can spend 100 days working on my graduation project in a 7-month period. In July, I will devote 4 days each week to my graduate project, and 1 day to my design job. From August through December, I will spend 3 days per week on the thesis project, and 2 days on my design job. In January, I will only work on the thesis project.

Appendix A

Project brief as approved at the start of the project

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

1. I think it's important for youth to play outside a lot and have "adventures" there. Especially as more and more children stay indoors and spend their time behind a screen. Natural playgrounds, as described in Herrington & Brussoni's (2015) research, are one of the most versatile places where the connection between children's health and development is strengthened. For example, outdoor play has a positive effect on children's cognitive and social-emotional development (Bento & Dias, 2017). Therefore, designing good playground equipment is important for children, and I would like to contribute to this.

2. I like working on projects that require taking into account a lot of different factors. For example, the playground equipment I will design must not only be durable, it must also be easy to (dis)assemble. Furthermore, it must be playable and invite children to play but it must also meet a lot of safety guidelines. Moreover, the playground must enrich the streetscape.

3. Sustainability is one of the most important topics in the design world. I think it is important to contribute to developments with a positive effect on the world.

4. I find materials science and the manufacturing of products enormously interesting. During this project I can study this in depth. I plan to visit one or more factories where they manufacture playground equipment and/or recycle products.

5. Outdoor play is for every age! Even I still enjoy climbing and going down a slide from time to time. Designing playground equipment suits me in this way. While designing I will ask myself several times: "Would I like to play here?"

Bento, G., & Dias, G. (2017). The importance of outdoor play for young children's healthy development. Porto Biomedical Journal, 2(5), 157–160. https://doi.org/10.1016/j.pbj.2017.03.003

Herrington, S., & Brussoni, M. (2015). Beyond Physical Activity: The Importance of Play and Nature-Based Play Spaces for Children's Health and Development. Current obesity reports, 4(4), 477–483. https://doi.org/10.1007/s13679-015-0179-2

As was concluded, in order to truly prolong product lifetimes, understanding consumers or users is crucial. This can be done through involving them in the (re)design process [15]. Therefore, a context mapping and co-design session were conducted together with schoolchildren aged 6-7, 8-10 and 11-12. The results of these sessions will also contribute to answering sub-question 3:

How can playground equipment contribute to increased outdoor play and physical activity and wellbeing among children?

Session method and structure

The session is based on the overarching design partnering method 'Cooperative Inquiry', in which adults and children work together to design something new [25]. The main structure is set up by means of the 'Guidebook Your Turn for the Teacher', which was provided by Mathieu Gielen during the course Co-design and Research with children. The guidebook is based on the results of the research project Co-design with Kids, funded by Dutch research organizations NRO and NOW, and provides support for building co-design processes that benefit both designers and the participants. This guide was especially helpful, as many examples were already focused on the design of a playground (Figure 93), showcasing its appropriateness in such a design session.

The goal of these sessions is to receive data regarding children's perception on, and behaviour towards playing outside and playing with playground equipment. Several exercises will both get them more acquainted with their own view on this topic, as well as prepare them for designing solutions which encourage children to play outside more. The results and conclusions from the design session will serve as inspiration for new playground equipment designs. Furthermore, as the exercises are linked to 'play functions', the most sought after functions will be incorporated into the design. This will ensure that the playground equipment will encourage children to play outside more, or at least play more on the playground equipment that they desire.

The session will consist of five parts, of which four are based on the first two parts of the 'activities design cycle' as proposed in the 'Guidebook Your Turn for the Teacher'. Going through only the first two parts of the design cycle was recommended when doing shorter sessions of ½ to 2 hours. As the playground design should enthuse a large and varying group of children, a large amount of qualitative data was collected. Multiple sessions with 6 classes of children ensured that the conclusions were rich with the data of 124 children. A session plan was constructed to visually convey the structure of the session (Figure 94) and was handed to the teachers of the children. The exercises build on the results of the previous exercises, taking the children through a logical design process step-by-step.

Theme, problem and research question

The theme of the design session will be 'exciting playground equipment'. The problem that the children will have to find a 'solution' for is the fact that children do not play outside enough. Exciting playgrounds can be a way to encourage children to go outside more, but what does the equipment look like or what does it need to do? The main question that they will have to find an answer to is:

How can playgrounds/ playground equipment be optimized to encourage children to play outside more?

This is quite literally a part of my own design project, and the generated ideas and solutions will serve as great inspiration.

Circularity and sustainability were not discussed in this design session, as the main focus is to find out what encourages children to play outside more. These results will be combined with the conclusions on circular and sustainable playgrounds, in order to design playground equipment that addresses both needs.

Data analysis method

The qualitative data that is gathered are the conclusions from each session, in which it becomes clear what the children's view is on playing outside, and which play functions and other ideas can contribute to encouraging children to play outside more.

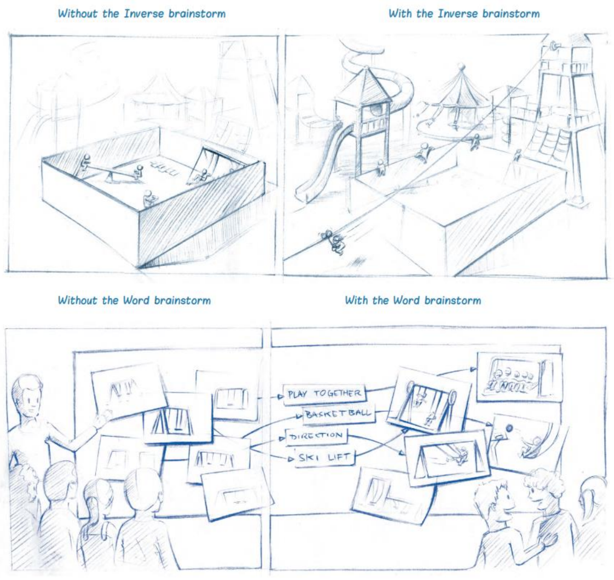


Figure 93: Playground design examples from 'Guidebook your turn for the teacher' [298]

The method used to analyse the data is Reflexive Thematical Analysis, with a more latent approach [30]. The purpose of this method is to develop patterns of meaning ('themes') across a dataset that address a research question. The developed themes here are based on preferred play functions and playground design solutions, based around the aforementioned research question.

This method consist of six phases

1. Familiarising yourself with the dataset
2. Generating labels/codes that capture and evoke important features of the data
3. Generating initial themes
4. Developing and reviewing themes
5. Refining, defining and naming themes
6. Contextualising the analysis in relation to existing literature

The conclusion of the conducted research will be a visual representation of the themes derived from the reflexive thematical analysis.

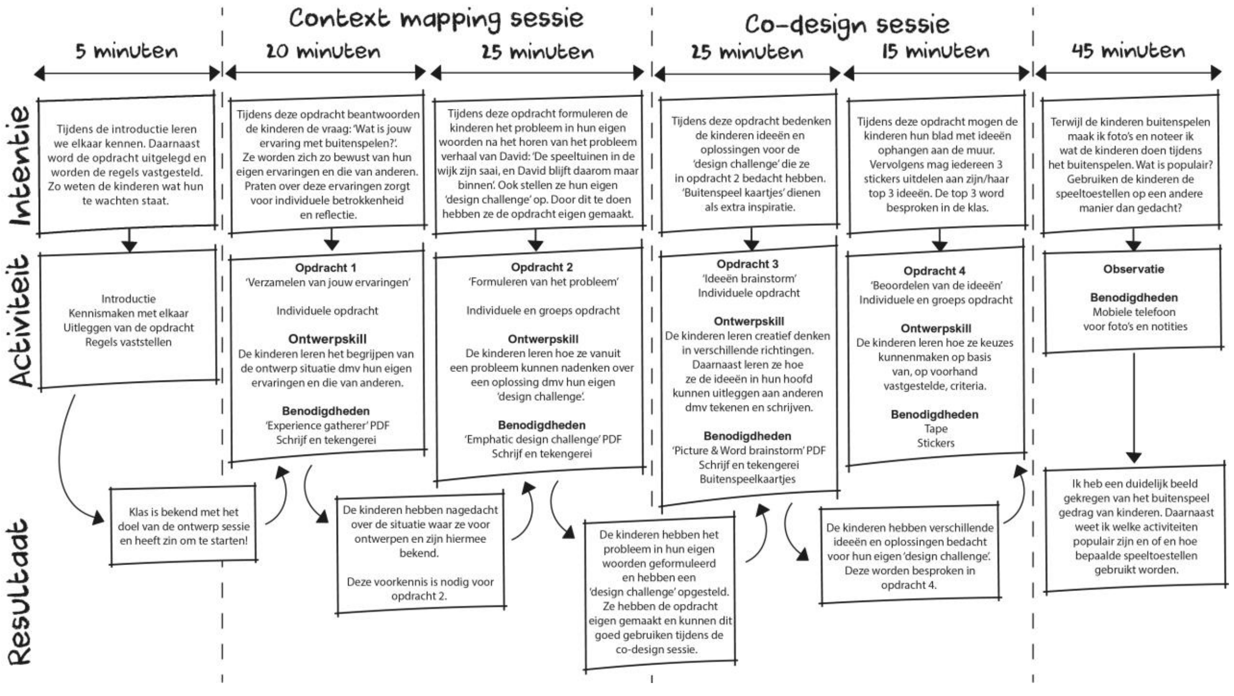


Figure 94: Session plan ((Dutch)

Design strategies
The design session should also be an interesting and educational experience for the children. As the session is most effective when the learning process is guided and promoted [31], the following design strategies were applied during the design activities:

- Clarifying learning goals and success criteria: A specific learning goal is given for each exercise and discussed beforehand. This is a fruitful way to make children's participation, especially in a school context, more meaningful as they will understand better what they are learning and what the focus of the exercises are [32].

- Demonstrations and practising with the aid of examples: Designing is a new activity for children. Therefore, the first two exercises (context-mapping session) will serve as a 'practice round', in which the children will get familiarized with the topic and design-thinking.

- Feedback so that the children can take the next step: After each exercise, an open discussion will be held to discuss the exercise, how it went and if the children are ready for the next exercise.

Learning goals (design skills)
- Develop empathy, in which the children empathise with and understand other users. They experience the problem themselves, investigate the users and context and actively seek input and feedback.

- Think in all directions, in which the children generate many, diverse and original ideas. They combine, associate and imagine. They seek inspiration in unusual places and look at problems from different perspectives.

- Bring ideas to life, in which the children learn to express and elaborate their thoughts and ideas in appropriate, meaningful ways and use tools such as stories, drawings, models and prototypes [26].

- Decide on your direction, in which the children organize their ideas and develop an overview of their project. They form an opinion about the essence of the problem and the desired quality of the solutions.

Research group
Children from the 5th and 6th class (8-10 years old) were selected as they are in the middle of the group of children that would play with playground equipment (4-12 years old). Furthermore, this age group can understand the tasks given to them and provide creative solutions as they are capable of creative thinking [33]. A design session was also conducted with a group of children from the 3rd (age 6-7) and 7th (age 11-12) class to see if there is a difference between age groups.

Informed consent
P. Jakobs has authorized to use the collected data and any images of the sessions and outside play, as long as the children are unrecognisable and the images are only used in the research as provided in this thesis [34].

Planning
The sessions were held on the 23rd and 24th of November and the 17th of January. Thursday the 23rd of November consisted of two morning sessions and an observation session with children from the 5th class (8-9 years old). Friday the 24th of November consisted of two morning sessions and an observation session with children from the 6th class (9-10 years old) (Table 8). Wednesday the 17th of January consisted of two morning sessions and an observation session with children from the 3rd (6-7 years old) and 7th (11-12 years old) class.

Date	Time	Activity
23 Nov	10:15-11:45	Context mapping and design session group 5A
23 Nov	11:45-12:30	Observations during outdoor playtime
23 Nov	12:30-14:00	Context mapping and design session group 5B
24 Nov	10:00-10:55	Observations during outdoor playtime
24 Nov	10:55-12:20	Context mapping and design session group 6A
24 Nov	12:40-14:00	Context mapping and design session group 6B
17 Jan	10:30-12:00	Context mapping and design session group 3
17 Jan	12:00-12:30	Observations during outdoor playtime
17 Jan	12:30-14:00	Context mapping and design session group 7

Table 8: Planning sessions

Introduction
In the introduction, the purpose of the session will be explained, as well as give the children time to get acquainted with the tasks at hand. Furthermore, rules will be discussed to decrease the change of children deviating from the exercises. Lastly, to motivate the children to participate, they will be told that their ideas might get used in the real design of the playground equipment.

Rules
1. The children can raise their hands to signal that they do not understand an assignment, have a question or want to talk about their ideas.
2. When you are asked to perform a task alone, try to do so. I really want to know everyone's individual experiences and ideas, and this can best be done when you are not discussing these with your classmates.

Duration: 10:15 – 10:20 | 5 minutes

Appendix B

Context mapping session, design session and playtime observations

Context mapping sessions
Exercises 1 and 2 are context mapping sessions. Context mapping is an explorative qualitative research approach which gives insight into the children's world of experience [28], and aims to create context awareness by eliciting emotional responses from participants, including users' concerns, memories, feelings and experiences of the explored contexts. Context mapping is based on a 'make and say' session where participants explore their experiences through creative tasks and discussions under guidance of a researcher. After the session, the collected data are further analysed and processed for application in the design process [29].

The context mapping session starts with the question: 'What is your experience with playing outside? By answering this question the children understand the context of the assignment and the use of the product 'playground equipment', as well as get inspiration for their own ideas and designs. As children are experts in 'playing with playground equipment' they have authentic perspectives, which can be conveyed through the context mapping session.

Exercise 1 | Exploring the problem | Experience gatherer
With this exercise, the children become aware of their own experiences and the experiences of others. Talking about these experiences ensures individuals engagement and reflection.
The question that is being answered in this first exercise is 'What is your experience with playing outside?'

Three considerations have been made regarding the set-up of this exercise:
1. The question is deliberately not focused on playground equipment, but formulated in a more broad sense. This has been done because it will be valuable to see what children's real experience is with playing outside, which can be both at school, in their backyard or in their neighbourhood. They might not even play on any equipment, but rather engage in different activities. Secondly, by keeping this first question broad, the children are not already narrowed down in their creative thinking. The activities that the children engage in that are not playground related could inspire them for example to incorporate these activities in playground equipment.
2. The 'problem' is deliberately not discussed yet in this first exercise. The children are directly related to the problem and telling them that 'children do not play outside enough' might already form the idea in their minds that this is also the case for them. By not discussing the problem, the children think about the context in a broader sense.
3. The children will perform this exercise individually. This way the children first consider their own experience, instead of copying one from a neighbour. Of course, they are allowed to write or draw collective experiences they had with friends or classmates, but the experience should come from themselves.

Learning goal/ developed design skill: Understanding the context by talking about their own experiences

Group or individual activity: Individual

Duration: 5 minutes explanation | 10 minutes writing and drawing | 5 minutes discussion

Supplies: Experience gatherer worksheet (Figure 95) and pens, markers and pencils

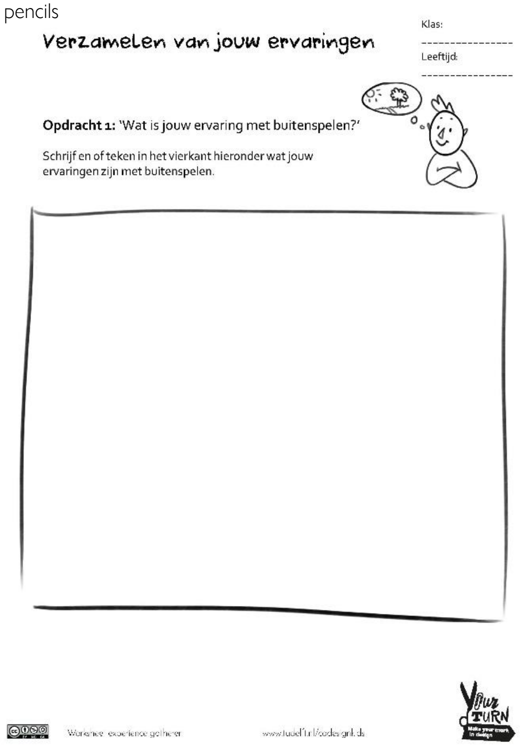


Figure 95: 6 Experience gatherer worksheet

Exercise 2 | Formulating the problem (in their own words) | Empathic design challenge
In exercise 2 the children will get familiar with the problem 'children do not play outside enough'. To ensure that the children will empathise with the problem of the real world users, a story will be told. By actively processing the story, the children think about what they want to achieve with their ideas or design for the users. Through this they feel involved in the problem and responsible for the result. A simplified 'research question' will also be discussed with the children, in order to make them understand what the design session is for:

What should a playground have or do to encourage children, like David, to play outside more?

As a group they will also determine a 'design challenge', which describes how they will go from the problem-space (present situation) to the solution-space (future situation) without thinking about concrete ideas or solutions.

The boy in the story, called David, will be 8 or 10 depending on the group. This will make sure the children feel connected to the main character.

Story
David is an 8 year old/ 10 year old boy who lives in a bit of a boring neighbourhood. He wants to do something active, go on an adventure together with his friends and have fun outside. However, his neighbourhood does not have many fun places to hang out and the playgrounds that are there are not exciting. Because of this, he does not know what do to, feels sad and stays inside.

After they hear the story, they are encouraged to retell it in their own words or experience, by means of the worksheet. After this, they have to think of a world or situation where this problem does not exist. This exercise will have to be performed individually, because it is important for the children to understand the problem in their own words and not be restricted by others.

After this, they have to formulate a design challenge, which will help them to really think about the design task at hand. They can do this in groups as this might be a more difficult task for them. It will be clearly explained that the challenge should state what the design should be able to achieve and who it is for, and that it should not describe a concrete solution or design idea yet. They will be encouraged to formulate design challenges that differ from other groups, as a personal point of view helps them to take ownership of the problem. If needed, an example of a design challenge will be given. However, efforts will be made to avoid this as the children could just copy the example, which is not the intention of this assignment.

Learning goal/ developed design skill: Develop empathy

Group or individual activity: First individual, then groups

Duration: 5 minutes explanation | 15 minutes writing and drawing | 5 minutes discussion

Supplies: Emphatic design challenge worksheet (Figure 96) and pens, markers and pencils

The empathic design challenge worksheet will be an A3 paper and folded through the middle to form two A4 sheets. The children will be instructed to perform the first part individually. They can then fold the paper open and perform the second part together with their group.

Appendix B

Context mapping session, design session and playtime observations

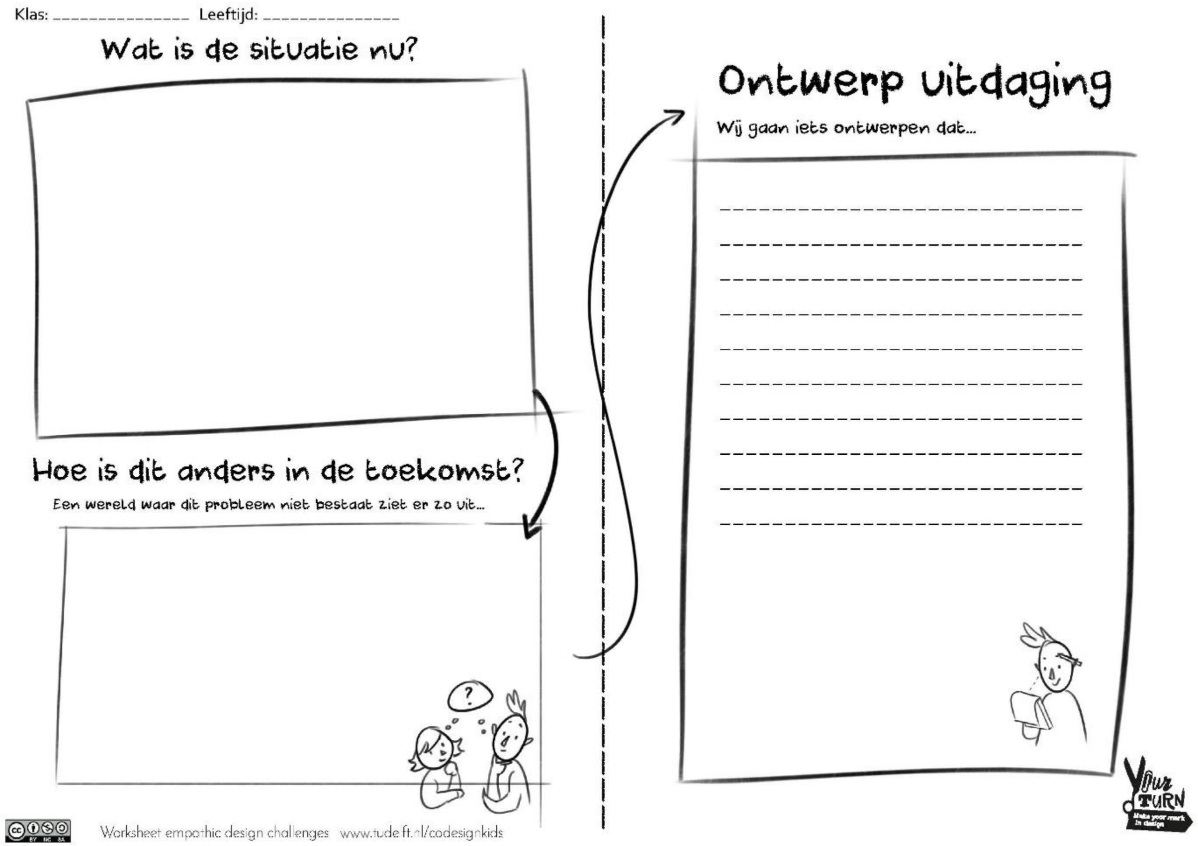


Figure 96: Empathic design challenge worksheet

Co-design sessions
After the context mapping session the children have expressed their own experience regarding the topic 'playground equipment'. They understand the problem 'children do not play outside enough' in their own terms, as they have formulated their own design challenge to solve the problem.

The children will use this acquired knowledge in the co-design session, in which they will design playground equipment or attributes which encourages children to play outside more.

Exercise 3 | Generating ideas/ concepts | Idea (picture & Word) brainstorm
During exercise 3 the children can use their acquired knowledge from exercise 1 and 2 to design solutions to solve the problem. Besides giving them the freedom to write down and sketch any ideas that they have, both pictures and words are provided to trigger their imagination and creativity if needed. The Play function cards are used for this, which were provided by M.T.R. Hettinga [27]. These cards, which have both words and pictures on them, encourage the children to think of more abstract ways to look at 'playing in a playground', which helps with coming up with appropriate ideas and solutions.

An A3 sheet of paper is provided on which the children can write or sketch any idea they come up with. When provided with the play function cards, the children are encouraged to only pick a top three. This way it also becomes clear which play functions, according to the children, will encourage children the most to play outside more. A special place on the worksheet is assigned to put the play function cards, in order to leave enough room for drawings.

After this creative session there will be no discussion, as the ideas will be discussed in exercise 4.

Learning goal/ developed design skill: Think in all directions and Bring ideas to life

Group or individual activity: Individual

Duration: 5 minutes explanation | 20 minutes writing and drawing

Supplies: Picture and word brainstorm worksheet (Figure 97), play function cards (Figure 8), glue and pens, markers and pencils

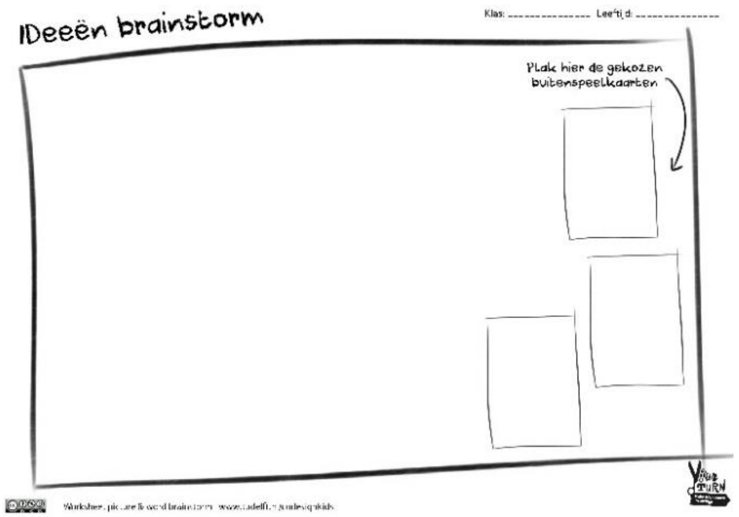


Figure 97: Picture and brainstorm worksheet

Exercise 4 | Selecting ideas/ concepts | Dot voting technique
After everyone has come up with their own ideas and solutions, it is time for them to select the ideas that they think solves the problem the most. They will be given the selection criteria: 'Which ideas can encourage children the most to play outside more?'

Everyone's 'picture & word brainstorm worksheet' will be hung on the wall. All the children can walk past all the ideas and vote for the ones that they think is best. Voting will be done by means of sticking dots on the worksheets. By sticking dots, the participants are not hindered by peer pressure as much as with a group discussion; they can do it by themselves. It will be emphasized that the children will have to make a choice on their own, without consulting with their classmates. They will be granted a total of three stickers, and they will have to give their top three each one sticker. They can not vote on their own idea. This enables them to think further about the ideas of others.

After they have all voted on the ideas, the top 3 ideas will be discussed. Questions like 'why do we think these ideas will solve the problem the most?' and 'can we maybe combine the ideas to solve the problem even more?' will be asked.

All ideas will serve as inspiration. However, by discussing a top 3 a combined conclusion, based on the opinion of all the children, can be formed.

Learning goal/ developed design skill: Decide on your direction

Group or individual activity: Group

Duration: 5 minutes explanation | 10 minutes choosing ideas and discussion

Supplies: Tape and stickers

Observation session
During the children's outside break, observations will be carried out. The goal here is to conclude on which activities or playground equipment is most popular. Furthermore, it will be interesting to see if certain equipment is used different as originally intended. These new ways of playing can be incorporated in the playground equipment design.

The children will be told that I am on the playground and that pictures will be taken. However, they were not told about the purpose of this, as they might behave differently because of this. They already know me from the design session, so I will not be a stranger to them.

Duration: 45 minutes

Supplies: Phone to use as camera and note-pad

Appendix C.1

Interview E. Huijgen (group advisor Socially Responsible Contracting and Procurement of the municipality of Leiden), 7th of August, 2023

What is your function within the organisation?
Commissioning: Set an example as a municipality so that other municipalities and the market follow. Furthermore, I am responsible for implementing the 6 'MVOI' themes in new tenders.

What should be different in current assignments regarding circularity?
Cause-effect: If you choose something now, what does that do for the future? Detachability, so you can introduce it in a different way. Pass-through is important. CO2 neutrality, in production and maintenance. But there is still little done in this field.

Do you have experience/examples of playground projects?
Trying to reuse playground equipment: lick of paint or refurbishing. I have not seen a circular playground design yet, more loose products (benches etc.). Children are the future, so properly introducing them to such a design is good.

What should I definitely take into consideration?
Integration of different themes is important. If you do something circular, you do something for the climate, CO2 reduction. Involve people who have a distance from the labour market. One should help the other to make even more impact.

Playgrounds often have to comply with manual and safety requirements, which can knock down the creative process. But the municipality is definitely open for conversation, so companies should come forward with their new ideas: One should be the pioneer.

Circularity must be in the DNA of the company. If a company is doing something different, explain why you are deviating. If it really means something we are open to it: The story is very important in tenders. Why does a company choose the balance they have chosen?
Also think about climate-adaptation (sun protection) and biodiversity.

Answers verified by E. Huijgen 24-08-2023

Appendix C.2

Interview M. Betgen (Play equipment manager municipality of Leiden), 8th of August 2023

What is your function within the organisation?
I am the play (and water) asset manager. I manage part of the investments.

Have any projects already made use of the Leidse ladder?
To be honest, I have not been directly involved into the construction of the Leidse ladder, so I am not sure.

What are interesting developments in playground equipment?
I really like a design by Aldo van Eik. He designed an eskimo hut made from stainless steel tubes. This thing is indestructible and can last 60/70 years. If one of the tubes gets bent, it is quite easy to repair or replace it. However, stainless steel converted into MKI value is not that good.

How often are playgrounds replaced?
We often replace playgrounds every 15 years. In some cases, this is a single piece of playground equipment, in others it is the whole playground. We have a contract with three contractors, including van Ee Speel. We replace roughly 20/30 playgrounds per year.

What materials do you see mostly in playground equipment?
Wood, metal and plastics.

What do you think would be positive developments regarding playground equipment in the circular economy?
I would like to see improvements in the end-of-life of playgrounds. We are thinking about the circular city, where we keep materials within the city and organise the waste flow ourselves. Leiden has its own waste collection service, so we already have some of the means. The transport would also stay low as a result. Residents want wooden appliances, which are soft and 'sustainable'. But I much more prefer stainless steel equipment, which lasts a very long time.

We also struggle with playing surfaces/ undergrounds. It would be ideal if biobased substrate has the same lifespan as the playground equipment.

Do you make use of playground depots?
Playground depots are used, but not much. We do work together with the DZB. They can repair part of the wooden playground equipment.

Answers verified by M. Betgen 25-08-2023

Appendix C.3

Interview T. Den Dulk (project coordinator water and play of municipality of Leiden), 22nd of August, 2023

What is your function within the organisation?
Executive side: I do the 'shopping' for Marcel. I am engaged in the design and construction of playgrounds and stimulate participation. I do the tangible things.

What do you think could be improved in terms of playground design?
Water management: If the community gets more involved in the playground, then you could do more with water in playgrounds. Now I do not dare to make a water playground in a public area because it cannot be maintained properly. More involvement means that more challenging equipment can be placed for the children to play with. Local residents are not empowered, but responsibility can be transferred.

During the meeting on the 15th of August, you talked about playgrounds in Paris and Berlin. What do you like about these playgrounds?
In Paris playgrounds are constructed in unity with its surroundings. Furthermore, when things get damaged it does not get repaired, but the damage creates part of the charm of the playground. Also, they think more about themes and how to deal with the imagination of children. I miss that in the Netherlands. In the Netherlands you see very few characters (statues or figures), which is a shame. We don't do this because we are afraid of these getting stolen or damaged due to vandalism. But when you look at playgrounds in Berlin for example, there is almost no vandalism. Furthermore, in Berlin people use playgrounds as much more than just places for children to play. Mothers use the area to host birthday parties for example. We need to create more involvement like this in the Dutch playgrounds.

Are any interesting business models utilized by playground developers?
Not really. Renting for example would be difficult as there may be an issue about ownership if an accident occurs. Less involvement can be felt by the municipality and responsibility can often be shifted away. Something I want to avoid at all costs, as I carry a great sense of responsibility towards the playgrounds within the city.

What should I definitely take into consideration?
- We often want to give residents a lot of choice in terms of playground layout, but that doesn't make them grateful because you can never please everyone. In Germany, playgrounds are laid out by data, which consists of raw materials used, how inclusive the equipment is, age structure of living environment, material and residual lifespan of equipment. This results in a playground which works much better in the neighbourhood. In the Netherlands we do not use enough of this data. Furthermore, the technical lifespan should not be the main line to replace a play area.
- See if smart equipment can collect energy form water or sunlight. If you're not allowed on a roof element, why not put a solar panel on it.
- Involving community and inclusiveness should be included and applied. The aim is for playgrounds to be used a lot again.

What do you think would be good circular design?
I am in contact with a supplier who is going to offer more and more modular pieces. It's like building playgrounds with lego pieces. The aim now is to let children exercise all muscle groups, not an Efteling design. With modularity, you get very far. You could use a computer model or AI where you can put needs, wishes and important data: 'I want 80% fantasy, 20% adventure, and a playground rolls out of that'.

What do you think is tricky about circular procurement?
Mainly the maintenance and the end-of-life is difficult and not thought of enough.

Are there materials that are used in playground equipment that you think work well in a circular economy?
Our playground equipment is mainly made from galvanised steel and wood (and sometimes aluminium). Stainless steel usage is very low. Wood fits well with 'natural' feel. However, we are somewhat critical of the lifetime of wood. Reusing galvanised steel is possible but does not happen much.

Answers verified by T. den Dulk 25-08-2023

Appendix C.4

Interview P. Roubos (technical consultant play municipality of Rotterdam), 10th of August 2023

What is your function within the organisation?
I have been working for the municipality of Rotterdam since 2000. I am the 'technical consultant for play' and I supervise the maintenance of playgrounds and whether this is carried out properly.

What is the main function of the playground depot?
We store old playground equipment. If people are interested, we repair the equipment and give it a new coat of paint if necessary. Furthermore, we make sure that when the unit goes out it meets the requirements. We employ a lot of people who have a distance to the labour market.
The municipality is often the owner of the playground, which allows us to perform maintenance tasks. This keeps the playgrounds save. We have often encountered that private owners perform inspections but do nothing with the recommendations the have received.

What is the biggest problem of the playground depot?
From interested parties, I often get wish lists of the parts they need and then reserve them. I can then talk enthusiastically about the play equipment and come up with creative solutions for using the play equipment. But often I never hear back from these people. That's why we have set a 3-month deadline on reserving parts.

There is some stuff stored online about the equipment at the depot. But this has to be kept up to date which is difficult. We have several people working who do not properly note the coming and going of play parts. The depot is also a very large area with little supervision, so things are sometimes 'stolen'.

We only repair/ refurbish play elements when there is an interested party (Rotterdam pays for the repairs). Therefore, most of the parts that we have looks dated or damaged, which is not attractive for potential customers.

What materials do you receive the most in the playground depot?
We mainly have RVS, as that materials lasts a very long time.

What requests do you receive the most?
Often people ask for equipment with a 'natural look', which is often wood. However, without the proper maintenance the wood rots and therefore we do not have much of this material in the depot.

What do you do with equipment that stays in the depot for a very long time?
We are currently dealing with a situation in which the depot has to decrease in size due to the construction of houses. Because of this we have to bring a lot of the equipment to the dump, which defeats the purpose of the depot. We are trying to look for a new location, but this is difficult.

What are difficulties regarding the removal of playgrounds?
A major problem with playground equipment removal is that the municipality is stuck with a contract that dictates that the contractor is responsible for removing the old playground equipment. This is often done with cost-saving as the main motivation, which results in contractors hiring the wrong demolishers who have no knowledge of demolishing playground equipment. A lot is pulled straight out of the ground which means it cannot be reused. Think, for example, of a metal duckboard, which is like a staple. If you pull it up out of the concrete, the two halves bend inwards, and you have nothing left. If you pulled it out evenly it would still be usable. However, demolishers don't benefit much from pulling it apart neatly because it takes more time and money. Moreover, stainless steel or copper can be sold to the scrapyard, making reuse unattractive. Contractors should therefore dispose of their playground equipment themselves and do this properly.

What do you think would be positive developments regarding playground equipment in the circular economy?
I think it would be interesting if a supplier made new playground equipment on our site from loose parts in our play depot, which we could then certify. This would be an efficient way to make something new from old materials.
Modular play equipment is also very interesting. We have teamed up with 3 suppliers, including Ijslander, to come up with the concept of 'Click & Play' which was first called 'Pluk & Play': You leave your frames or foundation in place but add or remove play elements for the next 20 years which enables the play equipment to grow, for use by toddlers until it becomes a hangout. This is a good development towards circularity.

Do you have any other recommendations for me?
The biggest problem is that people are too stuck in their own ideas on what a playground should be. For example, when people think of a swing, they don't fancy a hammock even though that works too. In addition, designers often don't know all the options to meet the play functions. Some designers would like a net structure, but that easily costs €80,000. If you look purely at the function, climbing, you can also fulfil it in a much cheaper way. That's why we made cards that describe different play functions, to which we can then link play equipment.

Consider the material of the underground and the way you construct your playground equipment on this underground. When using wooden elements, make sure you have metal feet under your wooden parts, (10cm above the ground). Do not put it on a sandy substrate or artificial grass (that contains sand). Wet feet with sand cause a lot of wear and tear. And sand is a bad surface in terms of hygiene.

Answers verified by P. Roubos 24-08-2023

Appendix C.5

Interview A. van Ee (owner van Ee Speel & project client), 10th of July 2023

Is the municipality of Leiden a big client of van Ee Speel?
The municipality is a good customer as we have several in this market. Not necessarily the biggest but a very valued one.

Why do you have an interest in the Leidse ladder?
My suspicion is that several local governments will embrace such a model. The municipalities have a good network and Leiden promotes its approach within municipal organisations on days like the Day of Circularity etc. The model also sounds logical and well-founded which makes it plausible to me that my clients will embrace it in the near future.

What is an indication for you that other municipalities will follow Leiden in their circular policies?
I think that was evident from the questions asked during the session on Circularity Day. Several municipalities are actively looking for ways to become fully circular in a timely manner. In tenders from municipalities, these requirements are also more common.

How many playgrounds do you place in the Netherlands yearly?
In Leiden every year about 7-10 in recent years. In total about 250-300 a year.

Where do you buy playground equipment?
We buy our playground equipment from companies in Europe, like the United Kingdom, Belgium and Germany based supplier. This company is quite transparent about where their materials come from. The wood that they use for example comes from Denmark.

Do you utilize a 'product as a service model'?
No because there is a problem in the legislation: the administrator is responsible for safety. Now, for example a teachers, concierges or a technical perform a daily check on the playground, which would not be possible if we had to do that.

What is the life expectancy of playground equipment?
15-20 years

What is the main reason for the removal of playgrounds?
1. End of technical lifetime: For Playdale equipment, with some maintenance this is 16-20 years, which is a common lifetime.
2. End of financial lifespan, which is often the case in municipalities.
3. Demographic development. 'It is no longer used'.

Do you do the removal of your playgrounds yourself?
At municipalities, we demolish ourselves, while at schools they often do it themselves, sometimes together with parents. Our people clear the playground and separate the materials as much as possible. Sometimes there is wood in the concrete. This is very annoying because wood cannot be filtered in the concrete shredder. We separate steel, concrete and wood. And then it goes to the processors of these materials or to the waste processor.

How often are things replaced, repaired?
Regular wear and tear: Every 3/4 years, cable or bolt connection must be replaced. Concierge also does repairs, like tightening a screw.

What are pain points during repairs?
The difficulties during repairs are e.g. that we have to dismantle large parts before an affected part can be replaced. Sometimes the ground even has to be opened. This is costly because we also have to open and glue the shock-absorbent ground cover of e.g. artificial grass. Devices from NOJEQ are easier to dismantle than those from e.g. Playdale, as they uses a lot more small parts. Even sidewalls sometimes consist of 4 parts plastic with a steel frame behind it. Really time-consuming to (dis)assemble. Europlay uses more prefabricated parts. Like floors and roofs. That works faster with assembly.

What are your thoughts on using only reused or recycled materials?
My main concern is quality. Furthermore, is the supply of this material stable and can we produce products with an identical amount of quality. Do we have to certify each individual playground equipment? Furthermore, Playdale and similar suppliers will have to adapt due to the laws and requirements set.

Answers verified by A. van Ee 30-10-2023

Appendix C.6

Interview S. van Huijstee (Quartermaster Circular Wood & Stone DZB Leiden), 14th of August 2023

What are the main duties of DZB Leiden?
We maintain playgrounds and perform tasks for the municipality of Leiden. We also perform repair and refurbishing services.

I had a conversation with Hermen van de Minkelis from Sloopcheck. He told me the following: *'Furthermore, I know a social work company that used to refurbish old playgrounds for reuse. They stopped doing it because replacement proved to be cheaper. The high yield of scrap metal is a major reason for this.*
Can you tell me more about this?
We used to do this a lot but are doing this less and less because it is cheaper to buy new playground equipment. Because of this we don't perform the same extensive repairs as we used to. For example, we used to have people who could do metalwork, but not anymore. A main reason is the changing demand from the municipality, where there is a difference between the policy department and the executive department. Playground repair would be a good initiative towards circularity, but often there is just no budget.

What do you do in terms of playground maintenance? And how does that work?
We perform periodic maintenance if this is not discussed within the warranty of playground equipment. For example, we replace small parts.

Do you also refurbish used wood?
Yes, we do. We often turn used wood into construction wood. We get wood from houses or barns retrieved by demolition companies. First, we remove any any metals like nails. We sand the old wood and saw it into the right measurements, after which it is sold by a timber business. Together with the business we determine whether the wood is still reusable. Wood is almost always reusable. We have received doors from 1920 that we can still reuse. In total, 60/70% of the wood that we receive can be reused.

What should I definitely take into consideration?
Look at joints: gluing, screwing, etc.. If you make wood-wood joints, you have fewer limitations. You can do it well with cnc-milling. However, you do have to consider moisture and the expansion of wood.

Answers verified by S. van Huijstee 06-09-2023

Appendix C.7

Conversation C. van Eykelen (consultant organic flows municipality of Rotterdam), 13th of July 2023

We have a depot to store playground equipment.

We do not support the use of plastic in outdoor areas because it results in microplastics.

We receive a lot of residual wood in the environmental park, which we would like to reuse. MDF is of bad quality and is often incinerated immediately. Other wood is shredded or also incinerated. We also get a lot of hardwood from, for example, tabletops, chairs and beds. We would like to see a solution for recycling/ reusing this. We have organised a challenge in cooperation with Blue City: The cross-layer wood hacketon. A lot of interesting insights came out of this.

Metal is never a problem. It has a positive residual value and is always in demand. Metals often go to the hardware store.

An interesting waste product is wool. We have a lot of sheep wool from Rotterdam, which is normally shipped to China. However, during the Covid pandemic this was no longer possible, and nowadays transport by sea container is too expensive. We then researched what you can do with sheep's wool. For instance, you can make felt, upholstery fabrics, or tweed from it. In the Netherlands, however, there is no industry that can process it. We don't have a washer or spinner. England and Ireland do.
Another interesting organic residual product is felled trees. Roughly 2,500 trees are cut down every year. This is because of rotting or being in the way because of the sewers. Now the felled tree goes with the contractor, but we want to change this. The municipality should retain ownership of this residual wood. Then it should not be shredded, but we should start using it for planks. However, this is an expensive step: Wood drying, sawing, etc.

A good tip I have is: Look at repair. We used to construct the casings of the district containers from metal sheets that were welded together. These containers are vulnerable because they are lifted out of the ground every week to be emptied, or because someone drives into them. And because they are welded it is difficult to repair separate elements. Now we construct houses with different plates, allowing them to be replaced individually.

Answers verified by C. van Eykelen 05-09-2023

Appendix C.8

Interview A. van Ee (owner van Ee Speel & project client), 17th of August 2023

What do you think are the most difficult points (from the Leidse ladder) to achieve as van Ee?
Point 4, design for multiple lifecycles. We do not have a plan or business model for this. Point 7, design for sustainable material use. We do not make use of a lot of biobased materials, except for wood. We do not make use of a lot of recycled materials, except for maybe some recycled plastic parts. Furthermore, we do not have a material passport or use MKI during the design process. We also do not make conscious use of concrete in accordance with the concrete agreement.

Do you repair everything yourselves? Or do you use organizations like DZB?
We do not make use of organizations such as DZB, but we would be interested, and I would like to have a conversation with Marcel Betgen about this. When there is a problem with the playground residents first report this to the municipality. Small things, like a splinter or loose bolt gets fixed by the organizations assigned by the municipality. More specific or bigger things are handled by van Ee Speel.

What is the lifespan of wooden elements?
Depends on the type of wood. Treated grene wood = 12-15 years.
Hardwood = 20 years.

What are the main causes for wood to decay?
The weather, wear and tear because of use, sand, moisture.

What happens to wooden elements after the lifetime of a playground?
Wood always goes to an incineration facility.

What are reasons to not use 'old' wood anymore?
Erosion, cracking and rotting. Firewood gets softer which makes it unsuitable.

What is the lifespan of metal elements?
The lifespan of metal elements, apart from wear and tear, is 70 years. Parts to which other parts are attached get 'tired' due to movement, which decreases the lifespan. But generally metal elements easily reach a lifespan of 40 years.

What happens to metal elements after the lifetime of a playground?
Stainless steel elements are sometimes reused.

Do metal pipes have a fixed width when used in playground equipment?
The steel industry sometimes has fixed values. 33mm is often the norm. Certain handrails do need a certain width: no more than 38mm otherwise children can't hold it.

What are important things to consider regarding fall height?
You have to consider the fall height. Fall height standard norm is described by EN1177. This is up to 60cm on a concrete floor, up to 1 metre for a sand ground, 1.50 meter or higher for natural grass or other shock-absorbent undergrounds, like wood chips or rubber.

What happens with rubber tiles when they are removed?
Second-hand tiles are used for the underground of horse stables. Old tiles are sometimes recycled again at the Granuband factory. Disadvantage is that transport is very expensive, and the quantity is too small to be profitable.

What does the demolition of playgrounds look like?
- Dismantling and separating materials from the soil. E.g., rubber tiles and concrete. It is also very common that we cannot separate concrete blocks from the wooden poles, leaving pieces of wood in the concrete. that is very annoying because that is harder to separate. You can separate steel and concrete better.
- Dismantling of steel parts of the appliance and separation of wood. Wood, plastic and metal are separated by us and disposed of in the relevant containers to the disposal company.
- Usually, our own people dismantle. it also happens in a schoolyard that local parties do it, sometimes as a sponsorship. In that case, we have no control over disposal. We sometimes hire contractors.
- Reselling old appliances does not happen very often. It is often damaged after dismantling and is no longer safe. As soon as we make adjustments, re-inspection is required. This quickly makes it expensive again for an appliance that is, say, 15 years old. Plus, it's difficult to estimate from the front how something will come out of the ground. Because you can't give the customer certainty.
- Reselling parts are mainly in stainless steel slides and rubber tiles. Stainless steel slides we sometimes apply 2nd hand in Robinia wood play equipment.

Would you be interested in reusing old playground equipment?
Well, it is difficult. Municipalities often organize mini competitions, where multiple companies have to pitch a new playground idea. We can promise them a lot of reused playground equipment for a low price, but the elements might get damaged during transport due to the quality of the materials or fall apart due to rot. We then must repair or even replace these elements, which is costly and not calculated into our initial price. Furthermore, it is not profitable to supply old playgrounds as the rotation would take too long. Also, reselling existing playground equipment is difficult because we usually don't have a drawing or a 3D image of it to easily incorporate it into the design. Plus, the uncertainty of the additional costs of repairs and sometimes inspections make it difficult for the sellers and the customer to agree on a price. Furthermore, technical people are expensive.

Answers verified by A. van Ee 30-10-2023

Appendix C.9

Interview J. de Krieger (Architect / Partner at Superuse, Co-Founder Blade-Made), 13th of September, 2023

Can you take me through the process of designing and building the blade-made playground?
First, we were in contact with wind turbine builders and everyone in the supply chain. Playgrounds was an interesting solution, and we investigated this further. We do the crude construction, like sawing the blades and an external party does the finishes. We reused the slides from the playground that was located where the Blademade playground is now.

Are you aware of the complications that arose afterwards?
Yes, we do. The research performed by Medici was executed per our request. However, we do not fully agree with their results. There definitely was a problem with the coating, but we have fixed that. In the end, materials will always cause certain problems.

What are your greatest learning points
Involve stakeholders early in the process. For example, the ‘keurmerk instituut’: ‘This is what we want to do, what do we need to consider?’. Have your dialogue in advance.
Regarding the blade made playground in Rotterdam, I don’t think we could have done a lot better.

What should I consider when designing playground equipment?

- Take wear spots into consideration.
- Think of a good maintenance plan.
- Read regulations carefully, do not read what it says but the intention, and devise smart designs accordingly.
- Mix devices and safety surfaces. All fall ground has a drawback, manufactured or placed. Peach pits or crushed shredded sports shoes can be a solution. You can also do a lot with drawings in the floor.
- Shade is important. Stainless steel slide gets hot. Put slide facing north and don't catch sun. Or think about shade cloths.
- Water square Rotterdam. Water storage combined with play area. Combine environment with play area.
- Think of what happens at the end-of-life.
- Playing is also trying out things that are not allowed. That is in the nature of children. Therefore, also look at how other groups will use the playground. How will loitering youth use it? Will they put graffiti on it?

Have you performed tests with children?
No, we haven’t, but we did ask about their opinions. We also visited existing playgrounds and analysed these. Playing consists of the following: Socialising, chasing each other (sliding is part of this) and swinging. Something fun that we came up with is a 5-sided football field. Because of this you can’t ‘win’ and the children have to make agreements regarding the rules of the game.

Answers verified by J. de Krieger 25-10-2023

Appendix C.10

Interview C. Kemp (circular developer Insert), 25th of July 2023

Does playground equipment get sold on your marketplace?
Quite rare. There is very limited circular thinking in that industry because of strict requirements.

Does Insert manage their own depots or do you outsource this? How many depots do you make use of?
We do not manage depots ourselves, but we do have agreements with partners. We make use of 5 to 10 depots which are located all over the Netherlands. These depots are for materials in which people have shown interest on the marketplace but cannot directly be transported to their new location

Are there inspections on the products posted on the marketplace?
Checking everything in advance would be too expensive for the sellers. Testing and guarantees are only considered when people are interested and are arranged between buyer and seller.

What would be your advice to van Ee/ playground supplier to make use of second-hand materials?
The most important thing is to chart what is available. Also look at the distance it takes to transport elements. Refurbishing playground equipment might be interesting. You could do this together with social workshops. Also, make sure that what you manufacture is easy to reuse (easy to dismantle, materials that last long, etc.)

What does Insert still want to improve? For example, Almere does not want to work with Insert because they want to keep everything local.
The biggest problem is that municipalities are not allowed to trade with the market. The municipalities of Amsterdam, Rotterdam and Breda for example use closed platforms. Because of this the out- and inflow of materials is lower than possible, which hinders the uptake of second-hand materials by companies. Furthermore, we also want to work with MKI’s. Also, we want to make improvements on the platform based on input from buyers and sellers, for instance make it easier for potential buyers to find the products they need on our platform, and suggestions from buyers on what makes it easier for them to publish materials. The closed platform is also constantly improving with the input from municipalities and other organisations who use it.

Answers verified by C. Kemp 12-09-2023

Appendix C.11

Interview J. Deurloo (Co-owner & Designer Beton-lab), 21st of September, 2023

Do you already make extensive use of recycled concrete?
All tiles we make from Novel Grey are made with recycled concrete. Only 20% of the concrete product can consist of recycled concrete in the construction sector. This is implemented because construction concrete needs to comply with a lot of rules and regulations. 20% recycled material = 20% less strong. We use a little bit more. Also, the world builds 5x more than what it demolishes, we don't have enough concrete. Now, rubble is used as a foundation under paving. But the techniques are getting better.

Can you use geopolymer concrete and recycled concrete together?
It can be done in theory. We have already experimented with it a few times. One disadvantage of geopolymer concrete is that it is not very fluid (viscous). The coarse rubble it incorporates causes that viscosity. Normally, a pebble or grain of sand is round, but recycled ones are not so round.

Recycled concrete appeals more to me: 'what you break down you reuse'. Geopolymer can be done with upcycling (incorporating remnants). Geopolymer can be made very strong, but using a fraction of cement is still most practical and safe. there is still a lot to be done with geopolymer concrete. Cement has been fully developed and is widely used. Fine to work with.

Do you think concrete has a good application in playground equipment?
Concrete is already used in the foundations of playground equipment and used for climbing or skating. So it is already being used. You can also make all kinds of shapes out of it. It doesn't break down, you don't demolish it easily. It would be fine in a playground. Interesting thought: children find abandoned cities or rubble interesting, here they go on adventures. Only drawback, you don't want to fall on it. With geopolymer concrete from waste products, it's important to know what's in it. Heavy metals you don't want in a playground.

What should I consider when designing with concrete?

- Constructively, it has to be right. Concrete is a composite: easy to break. Compressive strength is fine but tensile is not. If it has to carry things, it has to be reinforced.
- Sharp corner can easily break off.
- Design it robustly.
- Fabric forming, use fabric or column to form concrete.
- Wooden or steel mould, steel is expensive. Fix flexible materials and then pour concrete into it.

Is it possible to mass produce concrete objects?
Concrete is mass-produced a lot. Not by the kilo, but by the tonne. Also look at stamped concrete. Steel moulds can be used for mass production.

Could children burn themselves on concrete when it stands in the hot sun?
You would not burn yourself fast on concrete. Steel or rubber, for example, gets hotter. Also check out a skate park; that's all concrete and used all year round.

Do you know if structures/objects made from 100% GPC and rubble are also recyclable, where the separated material can be reused for new concrete?
Geopolymer concrete can be recycled and partly used in new concrete as it always remains reactive for x percentage; 50-70%. That is then somewhat lower quality, but still usable. In addition, special ovens are now being developed that can reverse chemical processes. And otherwise, it just becomes filler. This is similar to old cement stone which is also used as filler. it replaces part of the new cement because it has the same structure and size.

Answers verified by J. Deurloo 22-09-2023

Appendix C.12

Interview C. Vissering (Inspiration and technical information of sustainable, architectural concrete at Tektoniek), 11th of September 2023

Have you ever worked on/ seen a concrete playground project?
No, I haven't worked on or seen a project like that. However, there are projects where they constructed outdoor furniture from concrete. Look at 'The concrete Turn'.

How efficient can concrete be recycled into new granulate to be used in new concrete structures?
Concrete is already being 99.9% recycled. However, the application of recycled concrete in new concrete at the moment is low. Now, we mainly use it as the foundation under roads, because there is no other good solution for this. In building projects, they are hesitant to use it because it needs to be reworked (washed) before use in 'new' concrete and therefore it is more economic to just use it as foundation for roads. Also, if more than 30% recycled content is used, the rules for structural engineering need to be adjusted. A recommendation has been made as standardized document by CROW how to do that. For playground equipment this will not play such a big role, since the loads are less.

Do concrete structures often have steel reinforcement inside of them? And how does this influence the recycling process?
That depends on the kind of tension that is needed in the construction. Concrete can withstand a lot of pressure by itself, but not so much tension, as it is a brittle substance. So, you don't necessarily need reinforcement. You can compare structures that can be built with separate small elements. For example: You can build an arch, but a thin structure will have the tendency to fall. Recycling is not a problem, the concrete is 'crushed' during the recycling process and steel reinforcement can be taken out easily.

Is concrete recycling a heavy process (chemicals, CO_2 emission or energy use)?
No, I believe it is not that heavy on the environment. The concrete waste is crushed first. After this the 'granules' are washed and sieved in different gradations and can be reused again.

Is it possible to add biobased- or other materials to the concrete?
Yes, that is possible, but in terms of recycling I would not recommend that.

What is the life expectancy of concrete structures?
That depends on the structure & use-case. But they can exist for more than 100 years.

Could 'mosbeton' be used in the playground equipment?
Yes, Civil Engineering at TUDelft is doing something with that. You can do this in two ways. There is a special concrete mixture on which moss grows well. They apply this as a stucco layer. You can also work with reliefs to which moss or other plants adhere well. These reliefs are easy to apply in the mould of the concrete. Look at bark concrete, for example. However, moss can get slippery so I would not use it when climbing or walking is involved.

Are concrete structures easy to repair?
Yes, as you can just use new concrete paste to fill up cracks, dents or holes. If, for example, a corner has been broken of you could make a mould box around it and fill it with new concrete. The old and new concrete will stick to each other as if it is one piece.

How are concrete structures made?
Basically, it just involves a mould where the concrete is poured in. You can make this mould from different materials. An interesting feature of concrete is that it will copy the relief of a mould. Because of this, you can use different materials or reliefs to create unique and interesting designs.

Are there examples of modular concrete structures?
Yes. A lot of prefab concrete structures are already modular. Look for example at 'kanaal platen' (channel plates). Traditionally they pour concrete in between the junctures to fix them, but other types of fixation are being developed. You could connect modular elements with steel rods, but you can also connect them by giving them puzzle piece elements.

Is it possible to give concrete different colours?
Yes. Concrete consists of coarse stones (gravel), sand and cement (very fine microbeads). The cement is the glue, and the pigment sticks mainly to this, and not to the rest. As a result, during recycling, you get the gravel grain back without pigment. Besides pigments, you can also look at the natural colours of the gravel. For example, Norwegian white marble is used for white concrete. And when polished or another finish is applied the granulates will become visible and determine the colour partly.

Answers verified by C. Vissering 18-09-2023

Appendix C.13

Interview A. Alberda (Urban Mine), 20th of October 2023

Freement: Non-activated cement from concrete. How does it work?
Finest powder fraction Rutte produces, which contains the most unreacted cement. The composition of the freement may be influenced by the origin of the demolished concrete. When making a concrete mixture, the most durable option we are able to make for the cement/binder part is a combination with blast furnace slag, 10% Portland and Freement with some minor additions.

What % of a new concrete product can contain recycled/reused concrete aggregate? And how much recycled cement?
New inspection value this year: 100% of your gravel and 60% of sand may be replaced for recycled aggregate (which comes from the 'CROW-CUR Aanbeveling 127: 2021').

100% recycled aggregate is theoretically possible. It is mainly about how much adherent cement stone is still present to the gravel and sand fraction. More adherent cement stone is often higher water absorption and lower density. And so then you can apply less. During the recycling process, as much of this porous cement stone as possible is removed, reducing water absorption and increasing density. Depending on the debris we receive, it can be easier or harder to achieve this.

Is the urban mine located in the Netherlands?
Yes, it is.

Is all your extraction and production in the Netherlands?
At the moment, both extraction and production is in the Netherlands. We do have contact abroad. We can transport things by water and also have mobile recycling plants.

How does storing CO2 in concrete work?
Co2 treatment: You have gravel and sand, with a cement layer on top of it. When this gets in contact with CO2, CaCO3 is created. As this forms, the pores are filled, making the porous cement brick layer less porous. Consequently, there are fewer openings that absorb water like a sponge. This is because you need water in a concrete mix for your cement to react. In addition, you have to take into account the water that gets into the pores of the other materials. This is because this water is then no longer used for the cement reaction. For the Freegravel and Freesand options, this can be applied. Does often still fall under innovative blends that require material research depending on the customer. For the fine powder fraction, it really is indeed still at research level.

Do you have any other interesting insights for me?
Mainly thinking about the cycle of being able to constantly reuse the materials (gravel, sand, cement). The more other materials are added, the more complicated the recycling process may become, because other materials may influence the quality. The extent to which recycling is then still doable, especially for the cement fraction, has often not been considered.

Answers verified by Anna Alberda 31-10-2023

Appendix C.14

Interview Dr. F. Di Maio (research director Recycling Laboratory TUDelft), 20th of September 2023

Is C2CA used often?
At this moment they are used in a limited number of cases. For example, a basement in Green Village or a garage in Groningen. However, the C2CA produces high-quality aggregates. Not only coarse as conventional technologies do but also sand. the mechanical properties of concrete made using C2CA aggregates are comparable with concrete made with virgin aggregates. The main reason why recycled aggregates are not widely used is because people don't know what they are buying: "What is the quality?". However, C2CA Technology is currently addressing these issues to provide a solution to the concrete industry.

What is the environmental footprint of concrete recycling?
The environmental footprint is lower than conventional concrete. Of course, you need energy, but it results in retrieving a circular material. Also, sand is not abundant, so we found a solution for this.

Do you see an application for playground equipment?
Definitely! For sure, you can use it for everything. You don't need to use top-quality aggregate or a lot of cement because you don't need to hold huge loads. Of course, you need to ensure that the concrete is not contaminated with harmful pollutants like asbestos.

Is it possible to mix recycled aggregate with Geopolymer concrete?
Yes, you can use recycled aggregates for geopolymer concrete.

What happens with concrete waste without the recycler?
Usually, it is used for the foundation of roads. If that is not possible it is landfilled. It is not stored, because storing materials always costs money.

How many times can concrete be recycled? And how much percent of recycled aggregates can be used in new concrete products?
Concrete can be recycled many times. Of course, when concrete has to be made by recycled concrete, a suitable particle size distribution of aggregates has to be used. Suppose you have a large amount of recycled aggregates and sand from a concrete recycling plant which separate also sand (such as C2CA Technology). In that case, you can make a PSD all from recycled aggregates and then use 100% recycled aggregates to make concrete. By the norms, it is 20 or 30% at this moment in NL without the need to inform the customer (who buys concrete). It can be higher but then the customer has to be informed. From a performance point of view can be 100% (if the quality allows).

Cement cannot be recycled yet. Then, you have to use virgin cement. Some recycled fines can be mixed to make concrete but have limited binding properties.

Answers verified by Dr. F. Di Maio 22-09-2023

Appendix C.15

Interview J. van Herel (Cementbouw BV), 24th of October 2023

Our licensees consist of two divisions: Prefab paving production and supplying concrete mortar for in situ projects. We work with a select group of partners.

We are currently testing and improving self-compacting concrete (Mortar runs in all nooks and crannies, without vibration). If you look at precast geopolymer concrete products, 90% are self-compacting. Therefore, the moulds cannot be too complex.

The raw materials for the geopolymer concrete come from the Netherlands and Germany. We work together with Jansen BV and Rouwmaat who produce concrete mortar based on the Sqape technology. They can produce geopolymer concrete mortar which consists of 100% recycled aggregates and geopolymers.

Concrete can be coloured with for example iron oxides pigments. This is also possible for geopolymer concrete. The prices of the colour pigment do differ; Blue, for instance, is more expensive. Recycling concrete with different colours is not a problem, geopolymer concrete can be recycled like normal concrete. You can recover the aggregates.

During the production of geopolymer concrete, you start with a high pH, but it goes down, whereas with cement concrete, you start with a low pH value and this goes up. At the end, geopolymer and cement concrete have the same pH value. Therefore, this does not cause any problems during recycling. No separate certificates or factories are needed, you can recycle geopolymer concrete and cement concrete together. The aggregate released here can be used again for new concrete.

The colour of the recycled granulates will fade into the colour of the binder. You can see the colour of the gravel in concrete. The sand has more influence on the colour then the pigment.

The geopolymers binder as well as cement that have reacted to form a composite material cannot be used as binder again. It can be reused as a filler or fine aggregate.

Answers verified by J. van Herel 31-10-2023

Appendix C.16

Interview K. Wiersma (Theo Pouw), 19th of October 2023

Do you buy the geopolymer concrete or do you produce it yourselves?
We produce our own certified geopolymer concrete.

Do you also incorporate recycled aggregate in the geopolymer concrete?
Yes we do.

Is geopolymer concrete also recyclable where the aggregate can be reused in new concrete?
Yes that is doable. It follows the same principles as traditional concrete. You don't add a powder, but a liquid.

Do you process and produce everything in the Netherlands?
Yes, raw materials come from the Netherlands and the production is also in the Netherlands.

Do you also make products from concrete?
No, we only produce the concrete itself.

How many % of recycled aggregate do you use in your geopolymer concrete?
Depends on application. Can range from zero to 100%

What does your geopolymer concrete consist of? Why did you choose for this composition?
We use an alkaline activator, but are also experimenting with sulphate activation

Answers verified by K. Wiersma 30-10-2023

Appendix C.17

Interview P. Wolterink (Hoofd kwaliteit beton Rouwmaat), 30 October 2023

Do you work with geopolymer concrete?
Yes we do. We have four concrete plants, one of which also allows us to make Geopolymer concrete.

If so, do you make this yourselves or do you buy it?
We buy the raw materials and then make the concrete ourselves under licence from Sqape. Sqape is a joint venture between Cementbouw BV and Mineralz, which takes care of the compositions.

If you buy it, where does it come from?
Various suppliers.

If you produce it yourselves, is it done in the Netherlands?
The production takes place in the Netherlands. We have four concrete plants, one of which also allows us to make Geopolymer concrete. We buy the raw materials and then make the concrete ourselves under licence from Sqape. Sqape is a joint venture between Cementbouw BV and Mineralz, which takes care of the compositions.

Do the raw materials also come from the Netherlands? Both the recycled aggregate and the geopolymers.
Most of the raw materials come from the Netherlands.

What does your geopolymer concrete consist of? What is the choice behind this composition?
We don't give it away lightly. The choice comes from the client. We then work with Sqape to create a composition.

Do you use recycled aggregate in your geopolymer concrete? If so, how much %? How much % is theoretically possible?
We process concrete aggregate. Basically, you are allowed to substitute 30%. If you want more, this would have to be calculated by a structural engineer.

Is it possible to use only recycled aggregate in new concrete (i.e. without virgin aggregate)?
Yes, if agreed with the client and the structural engineer.

To what extent is geopolymer concrete recyclable? Can you break it back into its original components? To what extent can they be reused in new concrete? Can you recycle geopolymer concrete and traditional concrete together?
Geopolymer is 100% recyclable. We ourselves can crush it and reuse it again as aggregate. There are new techniques that take the crushing process even further and then recover original components.

Do you also make precast products/ concrete moulds, or do you collaborate with companies that can do this?
Yes we have a precast factory. The moulds are made elsewhere. Minor adjustments are done in-house.

Is it possible to colour geopolymer concrete?
Yes, that is possible.

To what extent does colouring concrete cause problems during recycling? Suppose you receive red and green concrete blocks, how does this mix into new concrete?
Because we recycle large batches of concrete, you don't really see a coloured batch back. The dye is bound and you don't see it again in new concrete. There is also colour difference in original aggregates.

For my graduation project, I want to design/develop playground equipment made of geopolymer concrete with 100% recycled aggregate. By playground equipment, I mean, for example, a climbing block with holes to sit in or protrusions to clamber on. Is it theoretically possible to achieve that with your company, with all raw materials coming from the Netherlands, and the recycling and production of the playground equipment also taking place in the Netherlands?
In theory, this is quite possible. I don't see any problem. Ofcourse in reality some work has to go in to achieve this, but it should be possible.

Answers verified by P. Wolterink 30-10-2023

Appendix C.18

Interview J. Smits (Managing Director & Finance Director Ecor), 4th of September, 2023

What are Ecor panels made of and how are they made?
Ecor only consists of 4 ingredients: cellulose fibres (often recovered from low-grade waste streams. For example, we are now making panels from cow dung), water, heat and pressure. The hydrogen bonds create the strength within our panels.

You mentioned the use of low-grade waste streams. What kind of materials do you use in your panels that come from this stream?
Well, we now use cow dung, but we have also used grass from Schiphol or hemp dust. we can actually process any cellulose fibre-rich waste stream. We have already tested more than 80 different streams.

Is it also possible to use wastepaper and cardboard?
Yes, that is possible, but it depends on the quality/ pollution of the waste material. We have performed tests with wastepaper, but the material was too polluted. We also mainly focus on agro-fibres.

How well can it be recycled?
The recycling process is fairly simple, as we do not make use of any additives or binders. We can shred the panels and use the material again to make a new panel. We have done tests in our lab where we were able to recycle our panels 25 times without losing quality.

How does your recycling process compare to that of for example wood regarding CO2 emissions and energy use?
As we use cellulose fibres, it is fairly simple to open up these fibres, as compared to wood recycling which takes a lot more energy to open up the fibres. However, you can hardly recycle wood. Most of this goes into the incinerator.

What is the life expectancy for Ecor panels?
Really depends on the application. Because we do not exist that long we also don't have physical proof of a high life expectancy. We always refer people to the material specifications.

Do you still produce the panels in the Netherlands?
We have our production facility in Venlo where we can produce 400,000 panels/ year. We also have a research lab in Venlo. We think it is important to solve the waste and CO2 crisis in the Netherlands. That is also what you see nowadays. It is more about the infrastructure within a country than that of the entirety of Europe.

What business model do you make use of?
We mainly focus on a local market (within a radius of 150 km), where we sell our panels, and the buyer is the owner of the panels. Sometimes our customers that buy the panels are also the ones providing us with the waste stream. That was the case with Schiphol.

Do you still collaborate with Niaga?
No. They do buy our panels and use their own additives. We now use a water-based glue, which makes recycling easier.

Do you make use of a material passport?
Not yet.

Is it possible to make 3D shapes?
Yes, that is possible to a certain degree. We have already developed curved panels. The main problem will be the durability of the panel, as the forces will divide among the different elevations of a 3D panel. Again, the application determines how far we can go.

Do you see an opportunity to use Ecor in playground equipment?
Ecor is 100% biobased and biodegradable and is therefore not suited for outdoor applications. I also don't know if a 100% biobased material that is weatherproof exists. What would be possible is to work together with Biopanel, where they provide the outside, and we the core, of the panel.

Answers verified by J. Smits 05-09-2023

Appendix C.19

Interview F. van Schoonhoven (Director Biopanel), 11th of September, 2023

How are the panels produced?
The panels are extruded.

Would it be possible to create 3 dimensional shapes?
Ribbing or a honeycomb pattern is possible through repressing. Our material can also be injection-moulded, but not for large products. For this, you should look at blow moulding. However, this is not possible because the material is very hard and therefore fragile. Conventional plastic in playgrounds is much more pliable. This may also make it not really suitable for playgrounds. For example, if I were to drive a nail through a sheet, it would break. Standard PLA would deform even at 60/70 degrees. We have a special recipe where the deformation temperature is at 110. So, we mainly designed for higher temperature resistance, but because of this there is a higher crystallinity, and the material breaks faster.

What is the life expectancy of your panels?
The biggest problem lies in plastic ageing. After 10 years, our boards have only 30% of their original strength, so we maintain a lifespan of 10 years. Traffic signs don't need to withstand a lot of forces, so this is not a problem, but for a playground it probably is. UV radiation in particular is killing because it degrades the material. However, painting of the material will expand the lifetime.

What happens to the panels after their initial lifetime?
There are two types of waste. We collect the cutting waste, and it goes back into the sheet plant. It is a thermoplastic, so it goes back into the material 1-to-1. Plates are sometimes taken back and reused in new plates. The ratio is often 30% old, 70% new. When a plate is 10 years old, it is composted along with a pile of organic waste from the municipality.

Do Biopanels also cause microplastics?
No. From petroleum, you can make products that break down into micro-plastics. PLA will break down into CO_2 in nature. PLA is also used, for example, in threads to close wounds in surgery. PLA is mainly lactic acid, which you produce yourself in your own muscles. So, your body breaks it down itself.

Do you see opportunities to use Biopanel in playground equipment?
I would like to give it a try. I see problems, but also solutions. We are now testing with paints that are completely biobased and biodegradable. These paints can make the biopanel enormously smooth so it can even be used as a slide. Moreover, it protects against the sun. To prevent breaking, you could make the sheets thicker. PLA chain is long and gets shorter by the sun, and then it becomes less strong. But a coating can inhibit this process. This coating could also be composted together with the biopanel. Above all, try not to mix materials. The world is dying of mixing.

Answers verified by F. van Schoonhoven 12-09-2023

Appendix C.20

Interview Dr. G. Ye (associate professor Section of Materials and Environment TUDelft, Chair research group Concrete Modelling and Materials Behavior), 31st of October 2023

The project for my master thesis is to design sustainable and circular playground equipment. I have looked at for example recycled or drop-in bioplastics and recycled wood, but geopolymer concrete with recycled aggregate seemed the most promising due to its durability, form freedom and ability to be recycled at the end-of-life.
Do you have thoughts on this application? Problems that might arise?
You have to be really clear about the requirements. What do you want to reach (strength for example)? I do not see a problem to use geopolymer concrete for these play blocks, but you have to do some experiments.

How does the overall Environmental Cost indicator of geopolymer concrete compare to other materials? Would you consider geopolymer concrete to be a material with an overall positive effect on the environment?
In the Netherlands there is the goal to reduce the CO_2 emissions by 65% by 2030, and to be CO_2 neutral by 2050. In their roadmap, geopolymer concrete is mentioned as one of the solutions towards this reduction [299].

How well can geopolymer concrete be recycled? Can you reuse the geopolymers in new concrete? Can problems arise during the recycling of geopolymer and traditional concrete?
Geopolymer concrete recycling and traditional concrete recycling follow exactly the same process, and the different materials within these two concrete mixtures won't cause a problem when new concrete is made from these recycled aggregates. Geopolymer concrete can definitely be used to create new concrete. Also, no problems arise when you recycle and use it multiple times.

Can you use colour in geopolymer concrete? Does this have an effect on the recyclability?
This is possible, and again does not differ from traditional concrete. There will be no problem during recycling. For example, if you add red aggregates to a new batch of grey concrete, the red will fade within the concrete and won't be visible anymore.

Do you see a future for geopolymer concrete? In what way?
This depends on the raw material that we are going to use. However, from what we have found in our research it has very good potential for the future. It is also very beneficial for society as it makes use of waste or industrial by-products as raw materials.

Answers verified by Dr. G. Ye 31-10-2023

Appendix C.21

Conversation E. van der Weij (Senior Specialist Materiaal Technologie Van Hattum en Blankevoort), 24th of October 2023

We have used geopolymer concrete a couple of times: Bridge piers, floor of sludge buffer tank, for Rijkswaterstaat fish passage cover plates (project Selectieve Onttrekking Ijmuiden), mock-up for quay wall (Port of Rotterdam).

In Dordrecht there is a location (Van Hattum en Blankevoort Zuid) that can make the moulds to build playground equipment.

There is no research done yet on the fatigue and lateral strength of geopolymer concrete. However, this should not be a problem for you as the equipment does not need to carry such heavy loads (as compared to buildings or bridges for example).

The price of geopolymer concrete is about 2 times more expensive than traditional concrete, but there is of course not one fixed price. It depends, among other things, on the amount, location and concrete quality. However, this doubling in price is mainly due to unfamiliarity among clients and still generic regulations.

A steel concrete mould can be used many times (a thousand times if they are properly maintained. The main cause of a defected mould is wear). There is no difference in using geopolymer concrete or traditional concrete. The only thing is that the type of mould-release agent is different for geopolymer concrete.

The equivalence between traditional and geopolymer concrete has been demonstrated by the 'Beton innovatie loket'.

"Independent experts have assessed an innovative product validated by the 'Betoninformatieloket' as a good and sustainable alternative to cement concrete. Thus, according to the validation, the assessed product performs as well as cement concrete. Thus, the product meets the conditions of the Concrete Agreement for making concrete more sustainable on four themes of CO2 reduction, circular economy, innovation and education and natural capital. In addition, the participating organisations that signed the Concrete Accord have agreed to accept the validated products as a reliable option in tenders." [184]

The geopolymer concrete that we use is produced by Jansen BV and Rouwmaat groep, which is based on the SQAPE technology.

Recyclability of geopolymer concrete has been examined by SGS Intron. The process is the same as for traditional concrete. Does not stand in the way of second life. Geopolymer and traditional concrete are recycled together as its practically not possible to separate geopolymer concrete from traditional concrete, because you can't see the difference between those types of concrete.

Coloured and non-coloured concrete is recycled together. This will not create complications as the amount of coloured concrete is very low.

Answers verified by E. van der Weij 30-10-2023

Appendix C.22

Interview S. Kamphuis (Strukton), 11th of October 2023

When you recycle concrete rubble you get the aggregate back, but can you separate it into its loose components such as sand and gravel?
Circuton is our recycled concrete. That consists of gravel, sand and cement stone. We can now replace 20% of the cement in concrete with circument (which is recycled cement stone).

Do you also use geopolymer concrete? And is this recyclable in its individual components and can it be reused?
Geopolymer concrete is a catalyst which consists of water glass, fly ash and blast furnace slag (this can come from stainless steel production, for example). A disadvantage of this, though, is that these raw materials are also used to produce blast furnace cement. So you are competing with the use of these raw materials.

Can you recover recycled aggregate from concrete by recycling and use it again in new concrete? Or is that material no longer of quality?
You can keep recycling aggregate. 30% is now allowed by law. We once built a platform with 100% recycled aggregate and it has been there for about 8 years now.

Answers verified by S. Kamphuis 02-09-2023

Appendix C.23

Interview G. van den Bosch (CEO Bosch Beton), 4th of November 2023

Do you work with geopolymer concrete?
Yes, through pilot projects.

Do you make GPC yourself or do you buy it?
We produce it ourselves with a technique that we have developed ourselves for the last 10 years.

Does the production of the geopolymer concrete happen in the Netherlands?
Yes, we do this in Barneveld.

Do the resources (aggregate and geopolymers) come from the Netherlands?
Yes, at least the organisations we buy it from are Dutch but I expect they also buy some of the "basic" raw materials elsewhere and so in all likelihood abroad.

What does your geopolymer concrete consist if? What is the choice behind this composition?
I can't tell you that for reasons of confidentiality. However, we are now participating in a pilot project facilitated by RWS and carried out by TNO, in which the different types of geopolymer concrete are coded in a certain way.

Do you incorporate recycled aggregate in your geopolymer concrete? If so, how many %? How many % is theoretically possible?
Not yet, mainly because we do not yet have our own technology 100% satisfactory, especially processability remains tricky/restrictive so we focus on that first and then switch to secondary raw materials if possible.

Is it possible to use only recycled aggregate in new concrete (i.e. without virgin aggregate)?
No, not at the moment. Mainly because we make structural concrete. In that, with "normal" concrete, we are also only allowed to replace 30% in accordance with current standards.

To what extent is geopolymer concrete recyclable: Can you break it back into its original constituents? To what extent are they reusable in new concrete? Can you recycle geopolymer concrete and traditional concrete together?
It is recyclable anyway, our geopolymer concrete does not leach out. At the moment, we haven't done enough research into this to really say anything about it that is substantiated.

Do you also make precast products/ concrete moulds, or do you have partnerships with companies that can do this?
We make these in-house. Often from metal or wood.

Is it possible to colour geopolymer concrete?
In theory it is. We haven't tested this yet.

To what extent does colouring concrete cause problems during recycling? Suppose you receive red and green concrete blocks, how does this mix into new concrete?
Very minimal I think, at the moment we also get aggregate from Scotland and Norway which is red and anthracite in colour but you see virtually nothing of that in terms of the appearance of the concrete, provided you wash out the concrete product which brings the pebbles into view.

For my graduation project, I want to design/develop playground equipment made of geopolymer concrete with 100% recycled aggregate. By playground equipment, I mean, for example, a climbing block with holes to sit in or protrusions to clamber on. Is it theoretically possible to achieve this with you, with all raw materials coming from the Netherlands, and the recycling and production of the playground equipment also taking place in the Netherlands?
That's pretty ambitious but theoretically feasible, I think.

As for feasibility, I think you have to ask yourself whether the cost/benefit balance is right, ultimately something like that has to be viable and I think that is only possible if it is scalable and therefore affordable, making it fit the (future) customer's needs.

At the moment, geopolymer concrete is really still a niche product, without any kind of certification and standardisation. Nevertheless, we have decided to do some pilot projects so that we can gain (practical) experience and know how the product behaves, but in low-risk environments. You could also consider doing it with low-cement concrete recipes and/or with hybrid concrete recipes, both are also possible with us, is more affordable and also achieve very nice MKI values.

Answers verified by G. van den Bosch 04-09-2023

Appendix C.24

Interview M. de Graaf (Rutte Groep), 9th of November

Do you work with geopolymer concrete?
Yes we do

Do you make GPC yourself or do you buy it?
We make it ourselves

If you buy it, where does it come from?
-

Does the production of the geopolymer concrete happen in the Netherlands?
Yes, this happens in the Netherlands

Do the resources (aggregate and geopolymers) come from the Netherlands?
Yes, they all come from the Netherlands

What does your geopolymer concrete consist of? What is the choice behind this composition?
Blast furnace slag/ free fine and activators. Free fine are our own released binder fractions from old concrete.

Do you incorporate recycled aggregate in your geopolymer concrete? If so, how many %? How many % is theoretically possible?
We only use recycled aggregates. So 100%.

Is it possible to use only recycled aggregate in new concrete (i.e. without virgin aggregate)?
Yes that is possible

To what extent is geopolymer concrete recyclable: Can you break it back into its original constituents? To what extent are they reusable in new concrete? Can you recycle geopolymer concrete and traditional concrete together?
It can be completely recycled and used again.

Do you also make precast products/ concrete moulds, or do you have partnerships with companies that can do this?
We produce our own prefab materials

How does Freement work? Have you used it in a real application? Are you more keen to use Freement or Geopolymer concrete?
Freement is a fraction of cement from old concrete that has not yet reacted in its lifetime, by releasing this fraction we have reactive binder again. Our preference is to act as sustainably as possible, and at the moment there is no significant preference in this.

How can you store CO2 in concrete? Is this already being done?
Aggregates are exposed to a high concentration of CO2, binding/fixing it in the "pores" of the material. This is still in the testing phase.

Is it possible to colour geopolymer concrete?
Yes this is possible

For my graduation project, I want to design/develop playground equipment made of geopolymer concrete with 100% recycled aggregate. By playground equipment, I mean, for example, a climbing block with holes to sit in or protrusions to clamber on. Is it theoretically possible to achieve this with you, with all raw materials coming from the Netherlands, and the recycling and production of the playground equipment also taking place in the Netherlands?
Yes that is definitely possible.

Answers verified by M. de Graaf 09-09-2023

Appendix D.1

Overview table of material data

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion (Not / Slightly / or / Yes / Moderately yes)
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-		
		Reduce number of materials	Does the material allow for form-freedom?	Moldability	1 (process not recommended) to 5 (excellent processability)		
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-		
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, limited use, acceptable, good or excellent		
			Is the material resistant to water and moist?	Water resistance	Unacceptable, limited use, acceptable, good or excellent		
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-		
	Climate change	Material production	If the material is used as virgin biobased material, does the production require low energy use?	Embodied energy, primary production	MJ/kg		
			If the material is used as virgin biobased material, does the production result in low carbon emissions?	Carbon footprint. Primary production	Kg/kg		
			If the material is used as virgin biobased material, does the production require low water use?	Water usage	L/kg		
		Material processing	Does the material processing require low energy use?	Coarse machine energy (per unit wt removed)	MJ/kg		
				Fine machine energy (per unit wt removed)	MJ/kg		
				Grinding energy (per unit wt removed)	MJ/kg		
			Does the material processing result in low carbon emissions?	Coarse machine CO2 (per unit wt removed)	Kg/kg		
				Fine machine CO2 (per unit wt removed)	Kg/kg		
				Grinding CO2 (per unit wt removed)	Kg/kg		
		Material recycling	Can the material be downcycled?	-	-		
			Can the material be recycled?	-	-		
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)		
			If recyclable: Can the material be recycled locally?	-	-		
			If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times		
			If recyclable: How many percent (%) of the PE product can consist of recycled materials?	Percentage recycled material in new product	Percent %		
			If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg		
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg		
		Material transportation	Is the material lightweight?	Density	Kg/m³		
			Is the material sourced locally?	-	-		
			Can the material be processed locally?	-	-		
	Ecological footprint	Land use	If the material is biobased, does it require a lot of land to be grown?	Land use	Ha/kg		
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits?	-	-		
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg		
			Does the material come from an abundant material stream?	-	-		
		Repairability	Can the material easily be repaired?	-	-		
		Maintainability	Does the material need low maintenance?	-	-		
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-		
			Does the material keep its original appearance after years of use?	-	-		
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9		
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	-	-		
			Does the material provide benefits to prevent harm?	-	-		
	User preference	Material coloring	Is it possible to colour the material without interfering with the recyclability?	-	-		

Appendix D.2

Overview table of material data | Comparing recycled plastic and drop-in bioplastic

				Recycled plastic (PP)	Drop-in bioplastic
Sustainable objective	Impact/ benefit category	Topic	Requirement	Explanation	Explanation
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	Recycled	Biobased
		Reduce number of materials	Does the material allow for form-freedom?	Similar, as drop-in bioplastics can be chemically identical to fossil-based plastics.	
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?		
			Is the material resistant to UV radiation?		
			Is the material resistant to water and moist?		
		Pollution	Does the material not pollute the environment?		
	Climate change	Material production & processing	-	When material production and processing of bio-PE and petroleum based PE are compared, bio-PE results in lower carbon emissions. When the energy use and carbon emissions of recycling of PP and producing of bio-PE (as these are both the birth step of plastic granulate to produce the PE) are compared, energy use is 250% lower and carbon emissions 200% lower of bio-PE when compared to PP [171,172,173].	
			Energy use recycling or production (MJ/kg)	PE: Recycling 26 – 28,6 Production 71,4 – 79,2 Granta Edupack, 2023) PP: 22,3 – 24,7 (Granta Edupack, 2023)	9,85 ([172])
			Carbon emissions recycling or production (kg/kg)	PE: Recycling 0,653 – 0,721 Production 1,79 – 1,99 (Granta Edupack, 2023) PP: 0,942 – 1 (Granta Edupack, 2023)	-1 ([172])
		Material recycling	Can the material be recycled?	When Bio-PE is used, it should be able to be recycled locally, at Save plastics for example, as is also the case with petroleum derived PE. Therefore, there is no difference between recycled plastic and Bio-PE [170]	
			If recyclable: Is recycling of the material common or in an infant stage?		
			If recyclable: Can the material be recycled locally?		
			If recyclable: How many times can the material be recycled (without losing quality)?	Polypropylene can be recycled a maximum of 20 times when an additive is incorporated [300]	Bio-PE can be recycled a couple of times [301]
			If recyclable: How many percent (%) of the PE product can consist of recycled materials?	Similar, as drop-in bioplastics can be chemically identical to fossil-based plastics.	
			If recyclable: Does the recycling process require low energy use?	As bio-PE recycling is identical to that of fossil-based PE, this is also similar to recycled plastic [170]	
			If recyclable: Does the recycling process result in low carbon emissions?		
		Material transportation	Is the material lightweight?	Similar, as drop-in bioplastics can be chemically identical to fossil-based plastics.	
			Is the material sourced locally?	The waste plastic can be sourced locally, as the Netherlands produces an abundance of plastic waste.	In theory the renewable biomass sources needed to produce bio-PE could be sourced in the Netherlands or Europe [302]
			Can the material be processed locally?	When bio-PE is used it should be able to be processed in the same manner as PE, and can therefore be processed locally [173]	
	Ecological footprint	Land use	If the material is biobased, does it require a lot of land to be grown?	-	Its use results in additional significant amounts of land and water use [174]
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits?	A benefit of recycled plastics compared to bioplastics is that it uses 'waste' materials, therefore retaining its value and diverting landfill waste [175]. A benefit of bioplastics compared to recycled plastics is that it captures carbon dioxide, therefore neutralising its carbon emissions [171]	
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Bio-plastic is more expensive then recycled plastic [171]	
			Does the material come from an abundant material stream?	There is an abundance of plastic waste, which is now mismanaged	The biomass needed for bioplastics is renewable and could therefore be abundant. However, it will have to be made new and this causes environmental problems [174]
		Repairability	Can the material easily be repaired?	In the construction sector, which shares similarities to playgrounds in terms of materials, conventional plastics (or recycled plastics) are preferred when compared to bio-plastics as its performance cannot yet be guaranteed [303]	
		Maintainability	Does the material need low maintenance?		
		Material lifespan	Does the material allow for a lifespan of at least 20 years?		
			Does the material keep its original appearance after years of use?		
		Product development	Does the material have a TRL of 7, 8 or 9?	Recycled PP has already been used by PE developers. | 9	- | 8 – 9 [304]
Provide Social benefits	User wellbeing	Bodily harm	Can the material cause burns when heated by the sun?	Similar, as drop-in bioplastics can be chemically identical to fossil-based plastics.	
			Does the material provide benefits to prevent harm?	Bio-plastics also cause microplastics [171] Bioplastics can cause mayor health problems [174]	

Appendix D.3

Overview table of material data | Reusing waste wood/ timber

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion ✗ or ✓ Not Yes ✗✗ ✓✓ Slightly Moderately yes ✗ ✓
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-	Derived from materials of biological origin (wood)	Biobased & Derived from Reuse
		Reduce number of materials	Does the material allow for form-freedom?	Moldability	1 (process not recommended) to 5 (excellent processability)	"It is easily machined, carved and joined, and – when laminated – it can be molded to complex shapes." (Granta Edupack, 2023)	2 – 3 (Granta Edupack, 2023)
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-	Wooden PE can get damaged from wear and tear, which is often caused in combination with the underlying substrate [45,97]	✗
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, limited use, acceptable, good or excellent	If untreated, UV radiation can cause damage to wood [185]	Good (Granta Edupack, 2023)
			Is the material resistant to water and moist?	Water resistance	Unacceptable, limited use, acceptable, good or excellent	If untreated, wood is not resistant to moisture [305]	Limited use (Granta Edupack, 2023)
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-	As timber is derived from materials of biological origin (wood), it will not pollute the environment.	✓
	Climate change	Material production	If the material is used as virgin biobased material: does the production require low energy use?	Embodied energy, primary production	MJ/kg	Reused waste timber is biobased, but in the discussed application not retrieved as virgin material, but by means of Reuse.	-
			If the material is used as virgin biobased material: does the production result in low carbon emissions?	Carbon footprint. Primary production	Kg/kg		-
			If the material is used as virgin biobased material: does the production require low water use?	Water usage	L/kg		-
		Material processing	Does the material processing require low energy use?	Coarse machine energy (per unit wt removed)	MJ/kg	-	1,24 – 1,37 (Granta Edupack, 2023)
				Fine machine energy (per unit wt removed)	MJ/kg		8,13 – 8,98 (Granta Edupack, 2023)
				Grinding energy (per unit wt removed)	MJ/kg		15,8 – 17,4 (Granta Edupack, 2023)
			Does the material processing result in low carbon emissions?	Coarse machine CO2 (per unit wt removed)	Kg/kg	-	0,093 – 0,103 (Granta Edupack, 2023)
				Fine machine CO2 (per unit wt removed)	Kg/kg		0,61 – 0,674 (Granta Edupack, 2023)
				Grinding CO2 (per unit wt removed)	Kg/kg		1,18 – 1,31 (Granta Edupack, 2023)
		Material recycling	Can the material be downcycled?	-	-	Wood can be downcycled, but not recycled [306].	✓ (Granta Edupack, 2023)
			Can the material be recycled?	-	-		✗ (Granta Edupack, 2023)
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)	-	-
			If recyclable: Can the material be recycled locally?	-	-	-	-
			If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times	-	-
			If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg	-	-
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg	-	-

Appendix D.3

Overview table of material data | Reusing waste wood/ timber

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion ✗ or ✓ Not Yes ✗✗ ✓✓ Definitely not Definitely ✗ ✓
Minimize Environmental impact	Climate change	Material transportation	Is the material lightweight?	Density	Kg/m³	-	850 – 1,03 e^3 (Granta Edupack, 2023)
			Is the material sourced locally?	-	-	"The mountain of wood that disappears in the incinerator every year in the Netherlands is huge: figures range from 2 million tonnes to even double this." [126] The municipality receives a lot of this material (wood), without a plan on how to reuse or recycle it [93]	✓✓
			Can the material be processed locally?	-	-	Waste wood can be processed locally by many different woodworking companies.	✓✓
	Ecological footprint	Land use	If the material is biobased, does it require a lot of land to be grown?	Land use	Ha/kg	Reused waste timber is biobased, but in the discussed application not retrieved as virgin material, but by means of Reuse.	-
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits (over a competitive counterpart)?	-	-	Wood stores CO2 [166]. When cascaded, it has more environmental benefits in comparison to the use of primary wood [307] The environmental cost indicator is very positive [126]	✓✓
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg	"Using recovered solid wood for material applications is economically viable and shows 32% lower costs compared to incineration." [307]	6,25 – 10 (Granta Edupack, 2023)
			Does the material come from an abundant material stream?	-	-	"The mountain of wood that disappears in the incinerator every year in the Netherlands is huge: figures range from 2 million tonnes to even double this." [126] The municipality receives a lot of this material (wood), without a plan on how to reuse or recycle it [93]	✓✓
		Repairability	Can the material easily be repaired?	-	-	"The choice of the appropriate material for wood structures repair is often a hard and complex decision." [308]	✗
		Maintainability	Does the material need low maintenance?	-	-	"Wooden products and constructions have to be regularly maintained with the aim to increase their lifetime." [308]	✗
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-	Reused waste timber could have a lifespan of at least 20 years, but this really depends on the type of wood, its condition and maintenance [44,45,66,97]	✓ 20+
			Does the material keep its original appearance after years of use?	-	-	Wooden outdoor products turn more grey as the years go by [309]	✗
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9	Waste wood has already been reused and refurbished for years on a small scale.	9
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	-	-	Wooden PE cannot cause burns.	✓✓
			Does the material provide benefits to prevent harm?	-	-	If the wood waste is turned into laminated timber, it can prevent harm [310]	✓
	User preference	Material coloring	Is it possible to colour the material without interfering with the recyclability?	-	-	-	-

Appendix D.4

Overview table of material data | Using recycled plastics

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion (✗ or ✓; Not ✗✗ / Yes ✓✓; Slightly ✗ / Moderately yes ✓)
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-	-	Recycled
		Reduce number of materials	Does the material allow for form-freedom?	Moldability	1 (process not recommended) to 5 (excellent processability)	As can be seen in the PE from Kompan, recycled PP plastic can be molded into any shape.	4 – 5 (Granta Edupack, 2023)
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-	Recycled plastic is resistant to wear and tear [311]	✓
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, poor, limited use, acceptable, good or excellent	PP needs UV protection (Granta Edupack, 2023)	Poor (Granta Edupack, 2023)
			Is the material resistant to water and moist?	Water resistance	Unacceptable, poor, limited use, acceptable, good or excellent	-	Excellent (Granta Edupack, 2023)
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-	Plastic playgrounds can discharge microplastics [93,312]	✗
	Climate change	Material production	If the material is used as virgin biobased material: does the production require low energy use?	Embodied energy, primary production	MJ/kg	-	-
			If the material is used as virgin biobased material: does the production result in low carbon emissions?	Carbon footprint. Primary production	Kg/kg	-	-
			If the material is used as virgin biobased material: does the production require low water use?	Water usage	L/kg	-	-
		Material processing	Does the material processing require low energy use?	Polymer extrusion energy	MJ/kg	"The energy consumption for the production of PVC, PP, and PE can be reduced by 74%–75% with the usage of 80% recycled material." [313]	5,87 – 6,49 (Granta Edupack, 2023)
				Polymer molding energy	MJ/kg		20,1 – 22,2 (Granta Edupack, 2023)
				Coarse machine energy (per unit wt removed)	MJ/kg		0,806 – 0,89 (Granta Edupack, 2023)
				Fine machine energy (per unit wt removed)	MJ/kg		3,78 – 4,18 (Granta Edupack, 2023)
				Grinding energy (per unit wt removed)	MJ/kg		7,09 – 7,83 (Granta Edupack, 2023)
			Does the material processing result in low carbon emissions?	Polymer extrusion CO2	Kg/kg	-	0,44 – 0,487 (Granta Edupack, 2023)
				Polymer molding CO2	Kg/kg		1,51 – 1,66 (Granta Edupack, 2023)
				Coarse machine CO2 (per unit wt removed)	Kg/kg		0,0604 – 0,0668 (Granta Edupack, 2023)
				Fine machine CO2 (per unit wt removed)	Kg/kg		0,284 – 0,313 (Granta Edupack, 2023)
				Grinding CO2 (per unit wt removed)	Kg/kg		0,532 – 0,587 (Granta Edupack, 2023)
		Material recycling	Can the material be downcycled?	-	-	Even though PP can be recycled, many complications make it difficult to actually execute [314,315]	✓ (Granta Edupack, 2023)
			Can the material be recycled?	-	-		✓ (Granta Edupack, 2023)
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)	-	2,57 – 2,84 (Granta Edupack, 2023)
			If recyclable: Can the material be recycled locally?	-	-	Plastic can be recycled in the Netherlands on a small scale [316].	✓
			If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times	Polypropylene can be recycled a maximum of 20 times when an additive is incorporated [300]	<20

Appendix D.4

Overview table of material data | Using recycled plastics

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion (✗ or ✓; Not ✗✗ / Yes ✓✓; Slightly ✗ / Moderately yes ✓)
Minimize Environmental impact	Climate change	Material recycling	If recyclable: How many percent (%) of the PE product can consist of recycled materials?	Percentage recycled material in new product	Percent %	Kompan offers different products with a recycled content between 25-100%. This depends on the recycled plastic, the size of the structure and the application [128] You can technically easily make products from 100% recycled PP [317]	25 – 100%
			If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg	-	22,3 – 24,7 (Granta Edupack, 2023)
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg	-	0,942 – 1 (Granta Edupack, 2023)
		Material transportation	Is the material lightweight?	Density	Kg/m³	-	895 – 909 (Granta Edupack, 2023)
			Is the material sourced locally?	-	-	The waste plastic can be sourced locally, as the Netherlands produces an abundance of plastic waste [318]	✓
			Can the material be processed locally?	-	-	Yes, some parts can be produced in the Netherlands. Hapro Plastic BV for example, produces plastic slides in their injection moulding plant in the Netherlands [319]	✓
	Ecological footprint	Land use	If the material is biobased, does it require a lot of land to be grown?	Land use	Ha/kg	-	-
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits (over a competitive counterpart)?	-	-	It has many benefits over using bio-based plastics [175] Evidence can be found that plastic recycling indirectly contributes to plastic pollution of the ocean [314,320]	✗
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg	-	1,51 – 1,73 (Granta Edupack, 2023)
			Does the material come from an abundant material stream?	-	-	There is an abundance of plastic waste, which is now mismanaged [319]	✓✓
		Repairability	Can the material easily be repaired?	-	-	Plastic playground repairs are time consuming, costly and do not leave an aesthetically pleasing result [97, 321,322]	✗
		Maintainability	Does the material need low maintenance?	-	-	"Apart from the rotating parts and cleaning it, not much has to be done." [63]	✓
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-	Recycled plastic could have a lifespan of at least 20 years [311,323]	✓ +-20
			Does the material keep its original appearance after years of use?	-	-	UV exposure will fade the colours of plastic [324]	✗
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9	Recycled PP has already been used by PE developers.	9
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	-	-	It is possible when the temperature of the plastic equipment gets very hot. However, this is less likely to be the case in the Netherlands as compared to Australia [271]	✗
			Does the material provide benefits to prevent harm?	-	-	Plastic playgrounds can discharge microplastics [93,312] "Even though negative health effects of microplastic exposure have not been confirmed in humans, this has been confirmed in animals, like marine life." [325]	✗
	User preference	Material coloring	Is it possible to colour the material without interfering with the recyclability?	-	-	The presence of coloured pigments in plastic recycling streams makes it harder to obtain recycled plastic with vibrant and distinct colours, and the resulting product is usually restricted to being used for grey or black products. This contributes to the demand for virgin, often oil-derived, plastic which can be coloured exactly as desired [326]	✗✗

Appendix D.5

Overview table of material data | Geopolymer with recycled aggregates

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion (✗ or ✓; Not ✗✗, Yes ✓✓, Slightly ✗, Moderately yes ✓)
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-	-	Recycled (aggregates are recycled from old concrete, geopolymers are derived from agricultural and industrial waste ashes).
		Reduce number of materials	Does the material allow for form-freedom?	Moldability	1 (process not recommended) to 5 (excellent processability)	Because geopolymer concrete starts of as a soft paste, it can be poured into any shape by means of custom-made moulds. Because of this, it is possible to create many different shapes and sizes, even slides ([138,157,180,181,182]	3 – 4 (Granta Edupack, 2023)
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-	Concrete PE will receive much less constant forces then traditional concrete structures, and therefore, similar to these structures, will be resistant to wear and tear due to use. Incorporating recycled aggregates does not cause problems regarding wear and tear [144] Geopolymer concrete is resistant to wear and tear, according to some studies even more so than traditional concrete ([147,148,150,182,184]	✓✓
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, limited use, acceptable, good or excellent	Concrete is mostly UV resistant, although long exposure can damage it over time [185]	Excellent (Granta Edupack, 2023)
			Is the material resistant to water and moist?	Water resistance	Unacceptable, limited use, acceptable, good or excellent	Concrete is mostly water resistant, although long exposure can damage it over time [186]	Excellent (Granta Edupack, 2023)
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-	Normally, mineral waste can cause environmental impacts. However, by integrating them in geopolymer concrete they are prevented from polluting soil and water [178]	✓
	Climate change	Material production	If the material is used as virgin biobased material: does the production require low energy use?	Embodied energy, primary production	MJ/kg	-	-
			If the material is used as virgin biobased material: does the production result in low carbon emissions?	Carbon footprint. Primary production	Kg/kg	-	-
			If the material is used as virgin biobased material: does the production require low water use?	Water usage	L/kg	-	-
		Material processing	Does the material processing require low energy use?	Coarse machine energy (per unit wt removed)	MJ/kg	In terms of using recycled aggregates, the carbon emissions are significantly reduced compared to OPC [143,327] In terms of geopolymer concrete, the carbon emissions are significantly reduced compared to OPC [150,151,152]	-
				Fine machine energy (per unit wt removed)	MJ/kg		-
				Grinding energy (per unit wt removed)	MJ/kg		-
			Does the material processing result in low carbon emissions?	Coarse machine CO2 (per unit wt removed)	Kg/kg		-
				Fine machine CO2 (per unit wt removed)	Kg/kg		-
				Grinding CO2 (per unit wt removed)	Kg/kg		-
		Material recycling	Can the material be downcycled?	-	-	Concrete can be recycled very effectively, even when the concrete structures have steel reinforcement in them [138,328] Geopolymer concrete can be recycled in the same way as traditional concrete, without the need of new methods or plants [145,157,158,159,181,182,190]	✓✓
			Can the material be recycled?	-	-		✓✓
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)	Recycling of (geopolymer) concrete is already being done, but recycled aggregates are not used on a big scale in the building sector due to strict regulations. It will be more common in the future due to new regulations and a growing interest [137,138,139]	13 – 14,4 % (Granta Edupack, 2023)
			If recyclable: Can the material be recycled locally?	-	-	Several concrete companies in the Netherlands have facilities where concrete is recycled and used in new concrete.	✓✓

Appendix D.5

Overview table of material data | Geopolymer with recycled aggregates

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation	Unit or Conclusion (✗ or ✓; Not ✗✗, Yes ✓✓, Slightly ✗, Moderately yes ✓)
Minimize Environmental impact	Climate change	Material recycling	If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times	Concrete can be recycled several times [143,144,181]	✓
			If recyclable: How many percent (%) of the PE product can consist of recycled materials?	Percentage recycled material in new product	Percent %	This depends on the quality of the recycled aggregates. 30% is allowed according to building legislations but 100% is possible and has already been applied [143,153,154,155,157,158,159].	30% is allowed according to building legislations 100% is possible
			If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg	-	0,774 – 0,853 (Granta Edupack, 2023)
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg	When compared to OPC, GPC production emits roughly 75-80% less carbon dioxide [150,152]	0,0868 – 0,1 (Granta Edupack, 2023)
		Material transportation	Is the material lightweight?	Density	Kg/m^3	Using recycled aggregates reduces the weight of the concrete structure as opposed to natural aggregates [193]	2,2e3 – 2,6e3 (Granta Edupack, 2023)
			Is the material sourced locally?	-	-	Both the recycled aggregates and geopolymers are sourced in the Netherlands and its surrounding countries [155,157,158,159]	✓✓
			Can the material be processed locally?	-	-	Multiple companies in the Netherlands can and have produced geopolymer concrete (products) in the Netherlands ([158,159,182,189]	✓✓
	Ecological footprint	Land use	If the material is biobased, does it require a lot of land to be grown?	Land use	Ha/kg	-	-
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits (over a competitive counterpart)?	-	-	Using recycled aggregate reduces the environmental impact as compared with OPC. Furthermore, waste is reused, eliminating the need for virgin materials [329] Geopolymer concrete reduces the environmental impact, such as CO2 emissions, as compared with OPC. Furthermore, as geopolymers are derived from waste, no virgin materials are needed [149,150,151,152,181,184,327,330,331,332]	✓
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg	Geopolymer concrete is twice as expensive compared to regular concrete. However, this is mainly due to the fact that it is not common (139,182]	Traditional concrete 0,0373 – 0,056 (Granta Edupack, 2023) 2x 0,0373 – 0,056 = 0,0746 – 0,112
			Does the material come from an abundant material stream?	-	-	Concrete is one of the most abundant resources in the world, and a big part of Dutch waste streams [177]	✓✓
		Repairability	Can the material easily be repaired?	-	-	Damage can be easily repaired [138,188] "When compared to cement-concrete buildings exposed to extreme conditions, GP (Geopolymer) is predicted to improve the service life of structures and perhaps save substantial repair and maintenance costs." [150]	✓✓
		Maintainability	Does the material need low maintenance?	-	-	Concrete structures need some maintenance [188]	✓
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-	Geopolymer concrete with recycled aggregate PE could have a lifespan of 50+ years [138,187]	✓✓ 50+
			Does the material keep its original appearance after years of use?	-	-	Any pigments or colors in the concrete surface will also break down (due to UV) resulting in color- fading or a faded appearance [185]	✗
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9	Structures made from geopolymer concrete with recycled aggregates have already been produced by several concrete companies.	9
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	-	-	You can not burn yourself on hot concrete. However, it could get too hot to play on (137,138]	✓
			Does the material provide benefits to prevent harm?	-	-	-	-
	User preference	Material coloring	Is it possible to colour the material without interfering with the recyclability?	-	-	It is possible to give concrete different colours, by means of coloured gravel or pigments, and will not become a problem during or after recycling, as the small amount of coloured aggregate will fade away amongst the greyish aggregate ([138,157,159,181,182]	✓✓

Appendix D.6

Overview table of material data | Comparing reused wood, recycled plastic and Geopolymer

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation			Unit or Conclusion: ✗ or ✓ (Not: ✗✗; Slightly: ✗; Yes: ✓✓; Moderately yes: ✓)		
						Reused wood/ timber	Recycled plastic	Geopolymer concrete	Reused wood/ timber	Recycled plastic	Geopolymer concrete
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-	-	-	-	Biobased & Derived from Reuse	Recycled	Recycled and derived from Reuse (aggregates are recycled from old concrete, geopolymers are derived from agricultural and industrial waste ashes).
		Reduce number of materials	Does the material allow for form-freedom?	Moldability	1 (process not recommended) to 5 (excellent processability)	It can be machined, carved and joined	As can be seen in the PE from Kompan, recycled PP plastic can be molded into any shape	Because concrete starts of as a soft paste, it can be poured into any shape by means of custom-made moulds. Because of this, it is possible to create many different shapes and sizes, even slides.	2 – 3 (Granta Edupack, 2023)	4 – 5 (Granta Edupack, 2023)	3 – 4 (Granta Edupack, 2023)
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-	Wooden PE can get damaged from wear and tear, which is often caused in combination with the underlying substrate.	Recycled plastic is resistant to wear and tear.	Geopolymer concrete is resistant to wear and tear, and according to some studies even more so than traditional concrete. Incorporating recycled aggregates does not cause problems regarding wear and tear.	✗	✓	✓✓
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, limited use, acceptable, good or excellent	If untreated, UV radiation can cause damage to wood	Recycled plastic needs UV protection.	Concrete is mostly UV resistant, although long exposure can damage it over time.	Good (Granta Edupack, 2023)	Poor (Granta Edupack, 2023)	Excellent (Granta Edupack, 2023)
			Is the material resistant to water and moist?	Water resistance	Unacceptable, limited use, acceptable, good or excellent	As it's a natural, porous material, wood can be susceptible to rot and decay if it's overexposed to moisture.	-	Concrete is mostly water resistant, although long exposure can damage it over time.	Limited use (Granta Edupack, 2023)	Excellent (Granta Edupack, 2023)	Excellent (Granta Edupack, 2023)
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-	As timber is derived from materials of biological origin (wood), it will not pollute the environment.	Plastic playgrounds can discharge microplastics.	Normally, mineral waste (agricultural and industrial) can cause environmental impacts. However, by integrating them in geopolymer concrete they are prevented from polluting soil and water.	✓	✗✗	✓
	Climate change	Material processing	Does the material processing require low energy use?	Combined value of processing	MJ/kg	-	The energy consumption for the production of PVC, PP, and PE can be reduced by 74%–75% with the usage of 80% recycled material.	Using both recycled aggregate and geopolymer concrete significantly reduces carbon emissions as compared to OPC.	25,7 – 27,75 (Granta Edupack, 2023)	37,646 – 41,59 (Granta Edupack, 2023)	2,06 – 2,28 (Granta Edupack, 2023)
			Does the material processing result in low carbon emissions?	Combined value of processing	Kg/kg	-	-		1,883 – 2,087 (Granta Edupack, 2023)	2,8264 – 3,1138 (Granta Edupack, 2023)	0,155 – 0,171 (Granta Edupack, 2023)
		Material recycling	Can the material be downcycled?	-	-	Wood can be downcycled, but not recycled. When downcycled, the wood is transformed to chips or fibres with reduced mechanical and other properties.	Even though PP can be recycled, many complications make it difficult to actually execute, like the limited recycling facility capacity and the quality and price of the recycled material.	Concrete can be recycled very effectively, even when the concrete structures have steel reinforcement in them. Geopolymer concrete can be recycled in the same way as traditional concrete, without the need of new methods or plants.	✓ (Granta Edupack, 2023)	✓ (Granta Edupack, 2023)	✓ (Granta Edupack, 2023)
			Can the material be recycled?	-	-				(Granta Edupack, 2023)	(Granta Edupack, 2023)	(Granta Edupack, 2023)
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)	-	-	Recycling of (geopolymer) concrete is already being done, but recycled aggregates are not used on a big scale in the building sector due to strict regulations. It will be more common in the future due to new regulations (Betoonakkoord for example) and a growing interest.	-	2,57 – 2,84 (Granta Edupack, 2023)	13 – 14,4 (Granta Edupack, 2023)
			If recyclable: Can the material be recycled locally?	-	-	-	Plastic can be recycled in the Netherlands on a small scale.	Several concrete companies in the Netherlands have facilities where (geopolymer) concrete is recycled and used in new concrete.	-	✓	✓✓
			If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times	-	Polypropylene can be recycled a maximum of 20 times when an additive is incorporated.	Concrete can be recycled several times.	-	<20	Several times
			If recyclable: How many percent (%) of the PE product can consist of recycled materials?	Percentage recycled material in new product	Percent %	-	Kompan offers different products with a recycled content between 25-100%. This depends on the recycled plastic, the size of the structure and the application.	This depends on the quality of the recycled aggregates. 30% is allowed according to building legislations but 100% is possible and has already been applied.	-	25 – 100%	30% is allowed according to building legislations (playgrounds are not included here) 100% is possible

Appendix D.6

Overview table of material data | Comparing reused wood, recycled plastic and Geopolymer

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation			Unit or Conclusion: ✗ or ✓ (Not: ✗✗; Slightly: ✗; Yes: ✓✓; Moderately yes: ✓)		
						Reused wood/ timber	Recycled plastic	Geopolymer concrete	Reused wood/ timber	Recycled plastic	Geopolymer concrete
Minimize Environmental impact	Climate change	Material recycling	If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg	-	-	-	-	22,3 – 24,7 (Granta Edupack, 2023)	0,774 – 0,853 (Granta Edupack, 2023)
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg	-	-	When compared to OPC, GPC production emits roughly 75-80% less carbon dioxide.	-	0,942 – 1 (Granta Edupack, 2023)	0,0868 – 0,1 (Granta Edupack, 2023)
		Material transportation	Is the material lightweight?	Density	Kg/m³	-	-	Using recycled aggregates reduces the weight of the concrete structure as opposed to natural aggregates.	850 – 1,03 e³ (Granta Edupack, 2023)	895 – 909 (Granta Edupack, 2023)	2,2e3 – 2,6e3 (Granta Edupack, 2023)
			Is the material sourced locally?	-	-	A lot of waste wood is incinerated (2 million tonnes each year in the Netherlands), instead of reused.	The waste plastic can be sourced locally, as the Netherlands produces an abundance of plastic waste.	Both the recycled aggregates and geopolymers are sourced in the Netherlands and its surrounding countries.	✓✓	✓	✓✓
			Can the material be processed locally?	-	-	Waste wood can be processed locally by many different woodworking companies.	Some parts can be produced in the Netherlands, like a slide.	Multiple companies in the Netherlands can and have produced geopolymer concrete (products) in the Netherlands.	✓✓	✓	✓✓
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits?	-	-	Wood stores CO2. Furthermore, reused wood has more environmental benefits in comparison to the use of primary wood. Also, the environmental cost of cross-layer wood from used material is 50% lower than that of cross-layer wood from new material.	It has many benefits over using bio-based plastics. However, plastic recycling indirectly contributes to plastic pollution of the ocean.	Using recycled aggregate reduces the environmental impact as compared with OPC. Furthermore, waste is reused, eliminating the need for virgin materials. Geopolymer concrete reduces the environmental impact, such as CO2 emissions, as compared with OPC. Furthermore, as geopolymers are derived from waste, no virgin materials are needed.	✓✓	✗	✓
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg	Using recovered solid wood for material applications is economically viable and shows 32% lower costs compared to incineration.	-	Using recycled aggregates and geopolymer concrete makes it more expensive than regular concrete. However, this is mainly due to the fact that it is not common.	Virgin wood 6,25 – 10 (Granta Edupack, 2023)	Virgin plastic 1,51 – 1,73 (Granta Edupack, 2023)	Virgin traditional concrete 0,0373 – 0,056 (Granta Edupack, 2023) 2x 0,0373 – 0,056 = 0,0746 – 0,112
			Does the material come from an abundant material stream?	-	-	A lot of waste wood is incinerated (2 million tonnes each year in the Netherlands), instead of reused.	There is an abundance of plastic waste, which is now mismanaged.	Concrete is one of the most abundant resources in the world, and a big part of Dutch waste streams.	✓✓	✓	✓✓
		Repairability	Can the material easily be repaired?	-	-	The choice of the appropriate material for wood structures repair is often a hard and complex decision.	Plastic playground repairs are time consuming, costly and do not leave an aesthetically pleasing result.	Damage can be easily repaired. Furthermore, geopolymer concrete improves the service life of structures as compared to traditional concrete.	✗	✗	✓✓
		Maintainability	Does the material need low maintenance?	-	-	Wooden products and constructions have to be regularly maintained with the aim to increase their lifetime.	Plastic PE needs low maintenance	Concrete structures need some maintenance.	✗	✓✓	✓
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-	Reused waste timber could have a lifespan of at least 20 years, but this really depends on the type of wood and its condition. Furthermore, waste wood has a bigger chance of erosion, cracking and rotting.	Recycled plastic could have a lifespan of at least 20 years.	Geopolymer concrete with recycled aggregate PE could have a lifespan of 50+ years.	✓ 20+	✓ +-20	✓✓ 50+
			Does the material keep its original appearance after years of use?	-	-	No, wooden outdoor products turn more grey as the years go by.	UV exposure will fade the colours of plastic.	Any pigments or colors in the concrete surface will also break down (due to UV) resulting in color- fading or a faded appearance.	✗	✗	✗
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9	Waste wood has already been reused and refurbished for years.	Recycled PP has already been used by PE developers.	Structures made from geopolymer concrete with recycled aggregates have already been produced by several concrete companies.	9	9	9
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	Thermal conductivity	W/m. C°	Wooden PE cannot cause burns.	It is possible when the temperature of the plastic equipment gets very hot. However, this is less likely to be the case in the Netherlands.	Concrete can not cause burns. However, similar to plastic, it can get too hot to play on.	✓✓	✗	✓
			Does the material provide benefits to prevent harm?	-	-	If the wood waste is turned into laminated timber, it can prevent harm, as laminated timber limits splits in poles, which can cause harm to children.	Plastic playgrounds can discharge microplastics which has a negative effect on the health of playing children.	-	✓	✗	✗
	User preference	Material coloring	Is it possible to colour the material without interfering with the recyclability?	-	-	-	When plastic with different colours is mixed during the recycling process, the new granulate will consist of a mixture of these colours which is often not preferred.	It is possible to give concrete different colours and will not become a problem during or after recycling, as the small amount of coloured aggregate will fade away amongst the greyish aggregate.	-	✗	✓✓

Overview table of material data | Comparing bamboo vs stainless steel poles

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation: Bamboo	Explanation: Recycled steel	Unit or Conclusion (✗ or ✓; Not ✗✗, Slightly ✗, Yes ✓✓, Moderately yes ✓): Bamboo	Unit or Conclusion: Recycled steel
Minimize Environmental impact	Material depletion	Origin of material	Is the material recycled, and/or biobased and/or derived from Reuse?	-	-	-	-	Biobased	Reycled
		Reduce number of materials	Does the material allow for form-freedom?	Machinability	1 (process not recommended) to 5 (excellent processability)	As bamboo poles are biological they are not consistent in size and shape. Even poles with the 'same' width can be shaped different from top to bottom [333] This makes it more difficult to implement them in a prefabricated product. However, solutions for this exist, like the Bamboo clamp connector. This has the ability to clamp bamboo poles, which makes using slightly different widths possible and eliminates the need for creating holes and using additional bolts. This in turn increases its durability. However, this is still in a prototyping phase [290]	Stainless steel poles can be extruded to any width and length. Curves can also be added in a pole, eliminating the need for additional couplers.	4 (Granta Edupack, 2023)	2 – 3 (Granta Edupack, 2023)
	Waste generation	Increase initial lifetime (prevent early disposal)	Is the material resistant to wear and tear due to use?	-	-	Its strength-to weight ratio is excelling that of materials like steel and timber. Bamboo is highly flexible and resilient, making it an ideal building material for structures that require a high degree of flexibility. [229,230,231]	Steel is durable. it has quite a long lifespan (40-70 years [97]). Because of this, playground equipment depots, like the one in Rotterdam, have a lot of stainless steel [45]. Its long life would also make it suitable for reuse, as is sometimes already done [97].	✓✓	✓✓
			Is the material resistant to UV radiation?	UV resistance	Unacceptable, limited use, acceptable, good or excellent	Treatments can increase the UV resistance.	-	Good (Granta Edupack, 2023)	Excellent (Granta Edupack, 2023)
			Is the material resistant to water and moist?	Water resistance	Unacceptable, limited use, acceptable, good or excellent	Treatments can increase the water resistance. "The natural antibacterial properties of bamboo make it an excellent material for use in humid and damp environments." [231]	-	Limited use (Granta Edupack, 2023)	Excellent (Granta Edupack, 2023)
		Pollution	Does the material not pollute the environment when it deteriorates?	-	-	-	-	-	-
	Climate change	Material Production/ processing	Does the material production require low energy use?	Embodied energy	MJ/ kg	"Bamboo has a comparable strength to steel. However, the manufacturing costs of bamboo are much lower when compared to steel as less energy is needed to harvest and transport bamboos. Even so, steel has the highest production energy-to-stress ratio when compared to other building materials. Bamboo has the lowest production-to-stress ratio, which shows a 98% energy saving when compared to steel structures." [230].		20,6 – 22,7 (Granta Edupack, 2023)	36,9 – 43,4 (Granta Edupack, 2023)
			Does the material processing require low energy use?	Embodied energy for coarse machining, fine machining and grinding (with extrusion for stainless steel)	MJ/kg			34,34 – 37,9 (Granta Edupack, 2023)	31,02 – 34,2 (Granta Edupack, 2023)
			Does the material production result in low carbon emissions?	CO2 footprint	Kg/kg	Bamboo can sequester large amounts of CO2 [230,334] "Steel manufacturing is an energy intensive process, with steel factories releasing significant amounts of CO2. Bamboo on the other hand has a much lower carbon footprint. Additionally, as bamboo forests absorb CO2 the overall offset of emissions is reduced." [236] "The ability of bamboo to sequester carbon during its growth is an important advantage over non-renewable materials such as steel. Because of this material property, bamboo delays the release of CO2 after its use phase. While steel-based scaffolding results in a significant amount of CO2 emissions during production, this is not the case for bamboo as the natural process to grow bamboo is integrated in different material flows and cycles." [235].		0,312 – 0,344 (Granta Edupack, 2023)	3,19 – 3,72 (Granta Edupack, 2023)
			Does the material processing result in low carbon emissions?	CO2 footprint for coarse machining, fine machining and grinding (with extrusion for stainless steel)	Kg/kg			2,578 – 2,846 (Granta Edupack, 2023)	2,32 – 2,57 (Granta Edupack, 2023)
		Material recycling	Can the material be downcycled?	-	-	Bamboo cannot be recycled. However, it can be used as fuel for energy generation.	Stainless steel can be recycled	✓	✓✓
			Can the material be recycled?	-	-			✗	✓✓
			If recyclable: Is recycling of the material common or in an infant stage?	Recycle fraction in current supply	Percent (%)	-	Recycling is common. Companies like Outokumpu use over 90% recycled material in their stainless steel [335]	-	36 – 39 (Granta Edupack, 2023)
			If recyclable: Can the material be recycled locally?	-	-	-	Companies like Metaalhandel, Schenk recycling and van Leeuwen Groep recycle stainless steel in the Netherlands [336,337,338]	-	✓✓

Overview table of material data | Comparing bamboo vs stainless steel poles

Sustainable objective	Impact/ benefit category	Topic	Requirement	KPI	Performance measure	Explanation: Bamboo	Explanation: Recycled steel	Unit or Conclusion (✗ or ✓; Not ✗✗, Slightly ✗, Yes ✓✓, Moderately yes ✓): Bamboo	Unit or Conclusion: Recycled steel
Minimize Environmental impact	Climate change	Material recycling	If recyclable: How many times can the material be recycled (without losing quality)?	Recyclability	Amount of times	-	Stainless steel can be recycled an infinite number of times without losing its strength and other properties [237,238,239,240]. Even so you can make "new stainless" from 100% recycled scrap [238]	-	✓✓
			If recyclable: How many percent (%) of the playground equipment product can consist of recycled materials?	Percentage recycled material in new product	Percent %	-	Companies like Outokumpu use over 90% recycled material in their stainless steel [335],while Metals Warehouse uses 60%, which is quite common in stainless steel products [240]	-	✓✓
			If recyclable: Does the recycling process require low energy use?	Embodied energy	MJ/kg	-	The energy intensity of virgin steel manufacture is around four times higher than that associated with recycling [339]	-	14,3 – 15,5 (Granta Edupack, 2023)
			If recyclable: Does the recycling process result in low carbon emissions?	Carbon footprint	Kg/kg	-	The production carbon coefficient of recycled steel is 40% of new steel [340]	-	1,13 – 1,21(Granta Edupack, 2023)
		Material transportation	Is the material lightweight?	Density	Kg/m³	-	-	602 – 797 (Granta Edupack, 2023)	7,61e³ – 7,87e³ (Granta Edupack, 2023)
			Is the material sourced locally?	-	-	Bamboo acquired from outside Europe, results in a higher environmental impact than using locally produced timber and steel materials because of the impact of transporting the bamboo materials, thus reducing their excellent environmental effect [229]. However, bamboo could be sourced in Europe, and in the future even in the Netherlands, as companies are investing in growing bamboo here [241]	Stainless steel scrap can be retrieved from the Netherlands.	✓	✓✓
			Can the material be processed locally?	-	-	Companies like Bamboe Bouw Nederland [341] and Bamboo Import [342] can produce custom bamboo products in the Netherlands.	Companies like TATA Steel and Keizersmetaal [343] can create stainless steel tubes in the Netherlands.	✓✓	✓✓
Provide Environmental benefits	All	All	Does the material provide any Environmental benefits?	-	-	Bamboo is the world's fastest growing woody plant as it matures in 3-6 years. Because of this, bamboo sequesters up to 12 tons of CO2 per hectare and produces 35% more oxygen than trees. [230,334]	Using recycled materials reduces the need for new virgin steel.	✓✓	✓
Provide Economic benefits	Developer perspective	Material acquisition	Does the material have a low acquisition price?	Acquisition costs	Euro/kg	-	-	1,25 – 1,87 (Granta Edupack, 2023)	3,87 – 4,28 (Granta Edupack, 2023)
			Does the material come from an abundant material stream?	-	-	Bamboo has to be specifically grown, while recycled stainless steel scrap can be retrieved in the Netherlands.		✗	✓
		Repairability	Can the material easily be repaired?	-	-	Bamboo structures are simple to construct and are resistant to wind and even seismic forces, while at the same time being easily repairable if damaged [344]	Due to its durability, steel tubes do not need much repairs	✓	✓✓
		Maintainability	Does the material need low maintenance?	-	-	Compared to a steel playground, bamboo needs a lot more maintenance [345]	Due to its durability, steel tubes do not need much maintenance	✗	✓✓
		Material lifespan	Does the material allow for a lifespan of at least 20 years?	-	-	Bamboo in construction offers benefits such as prefabrication, simple assembly, simple replacement of structural parts, and moreover, the bamboo elements could easily be dismantled and reused for another application [232] Kaminski [346] concluded in his study that the most effective treatment can give bamboo a lifespan of 20+ years, when it has an outdoor application (with rain and sun) and is placed above ground (i.e. secured on a framework or holder). However, this was concluded in a hot and wet tropical climate. In the Netherlands this could be slightly more. Yadav & Mathur [347] conclude on a lifespan of 40 years.	-	20-40 years [346]	40-70 years [97]
			Does the material keep its original appearance after years of use?	-	-	The discoloration of the bamboo poles will happen and eventually they will grey, this is a natural process [348]	-	✗	✓
		Product development	Does the material have a TRL of 7, 8 or 9?	TRL	Value 1 to 9	Both materials have applications in playground equipment.		9	9
Provide Social benefits	User wellbeing	Bodily harm	Does the material not cause burns when heated by the sun?	Thermal conductivity	W/m. C°	As bamboo has very low thermal conductivity, it will not get very hot and will not cause burns.	With steel, there is even a risk of burns due to its high conductivity [350] You would not burn yourself fast on concrete. Steel gets hotter [351]	✓✓	✗
			Does the material provide benefits to prevent harm?	-	-	Even though bamboo is smoother than wooden poles, it can still cause splinters [349]	-	✗	✗

Appendix E

Playground equipment on site

1. Climbing bench

2. Ping-pong table

3. Net swing

4. Tumble bar

5. Sitting wall

6. Climbing parkour 1

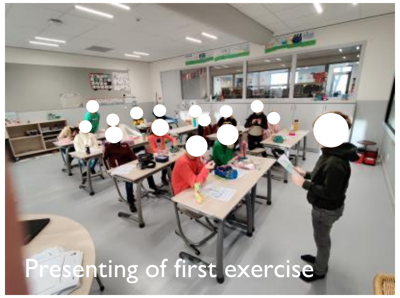
7. Climbing parkour 2

8. Climbing castle + slide

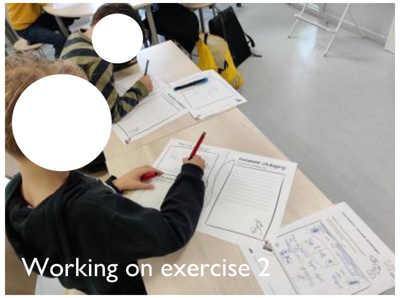
9. Monkey bar

Appendix F

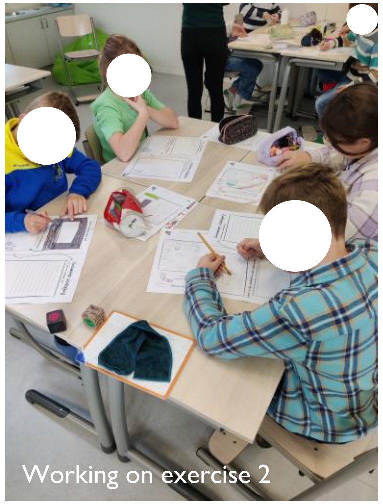
Context mapping and design session images



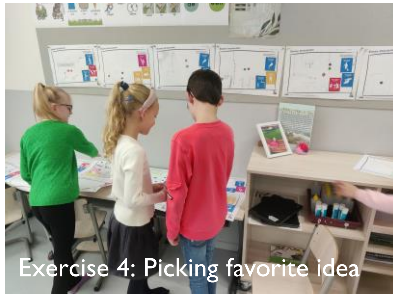
Presenting of first exercise



Working on exercise 2



Working on exercise 2

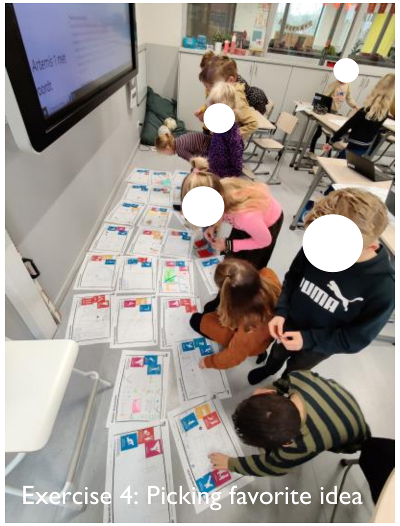


Exercise 4: Picking favorite idea

Working on exercise 3

Working on exercise 3

Exercise 4: Picking favorite idea



Exercise 4: Picking favorite idea

Observation of activities during outdoor playtime

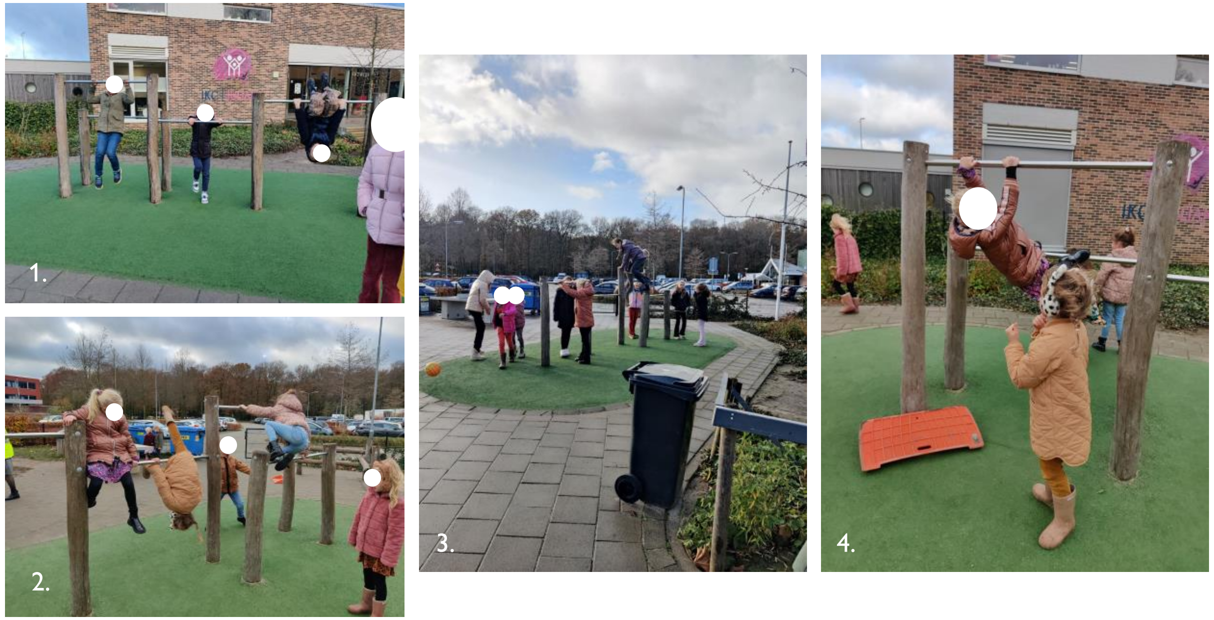
Swinging

Hiding

Appendix G

Observation of activities during outdoor playtime

Tumble bars

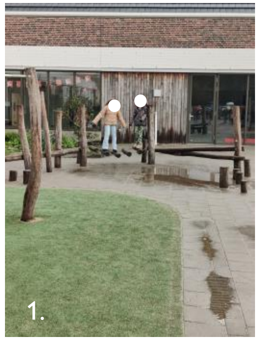


Challenges

Appendix G

Observation of activities during outdoor playtime

Climbing



Tag/ running

Playing with snow/ ice

Hanging out


1.


2.


3.


4.


5.


6.


7.


8.

Appendix G

Observation of activities during outdoor playtime

Soccer


1.


2.


3.

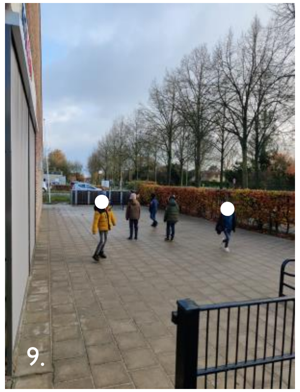

4.


5.


6.

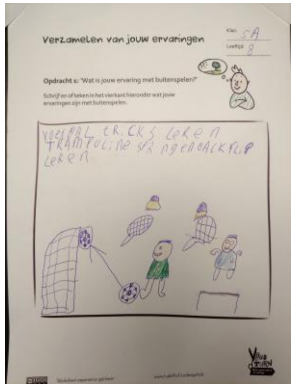
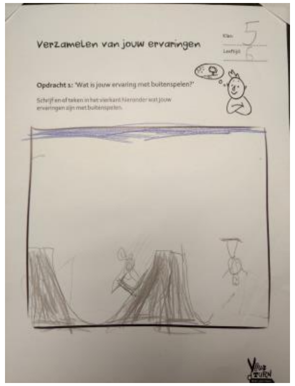
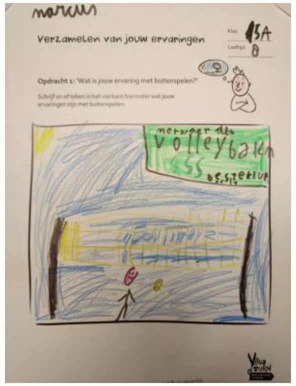
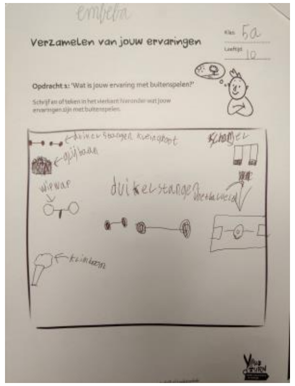

7.

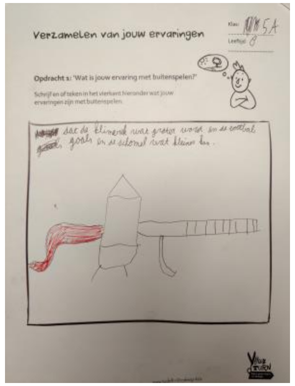
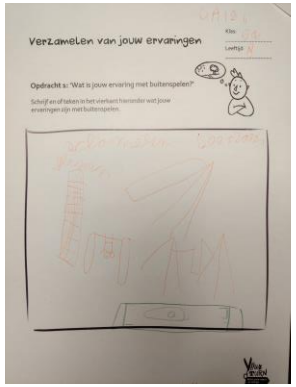
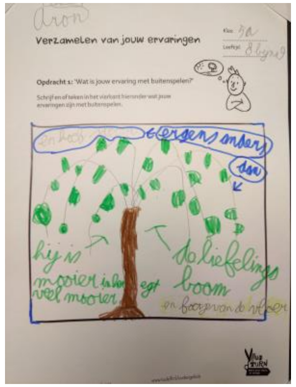
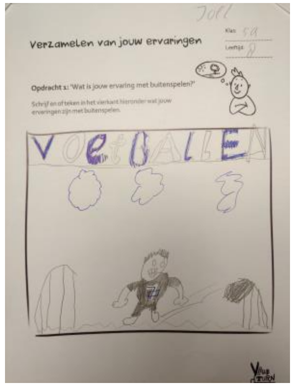
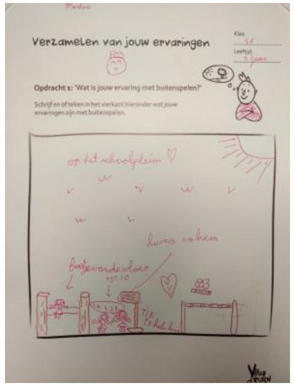
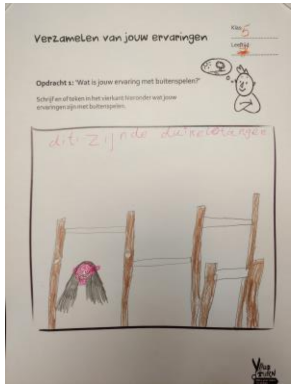
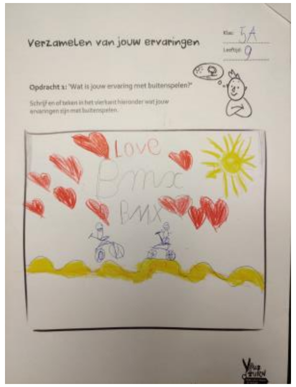

8.


9.

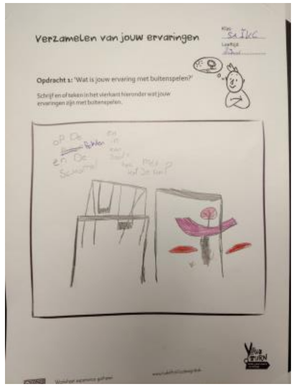
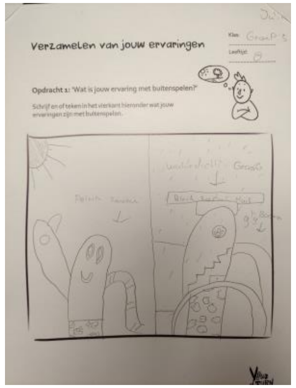
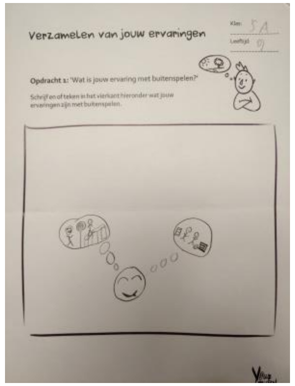
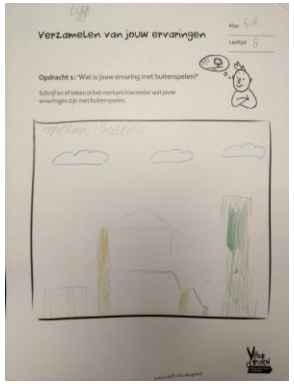
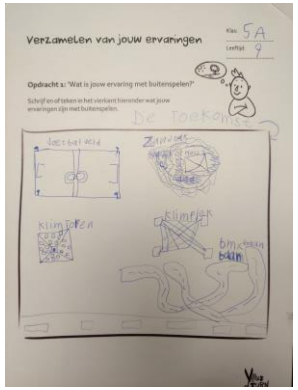
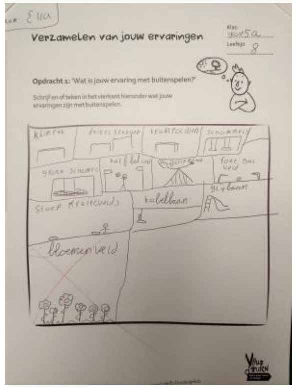
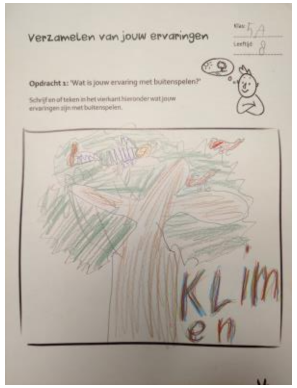

10.

Session 1 | Experience gatherer

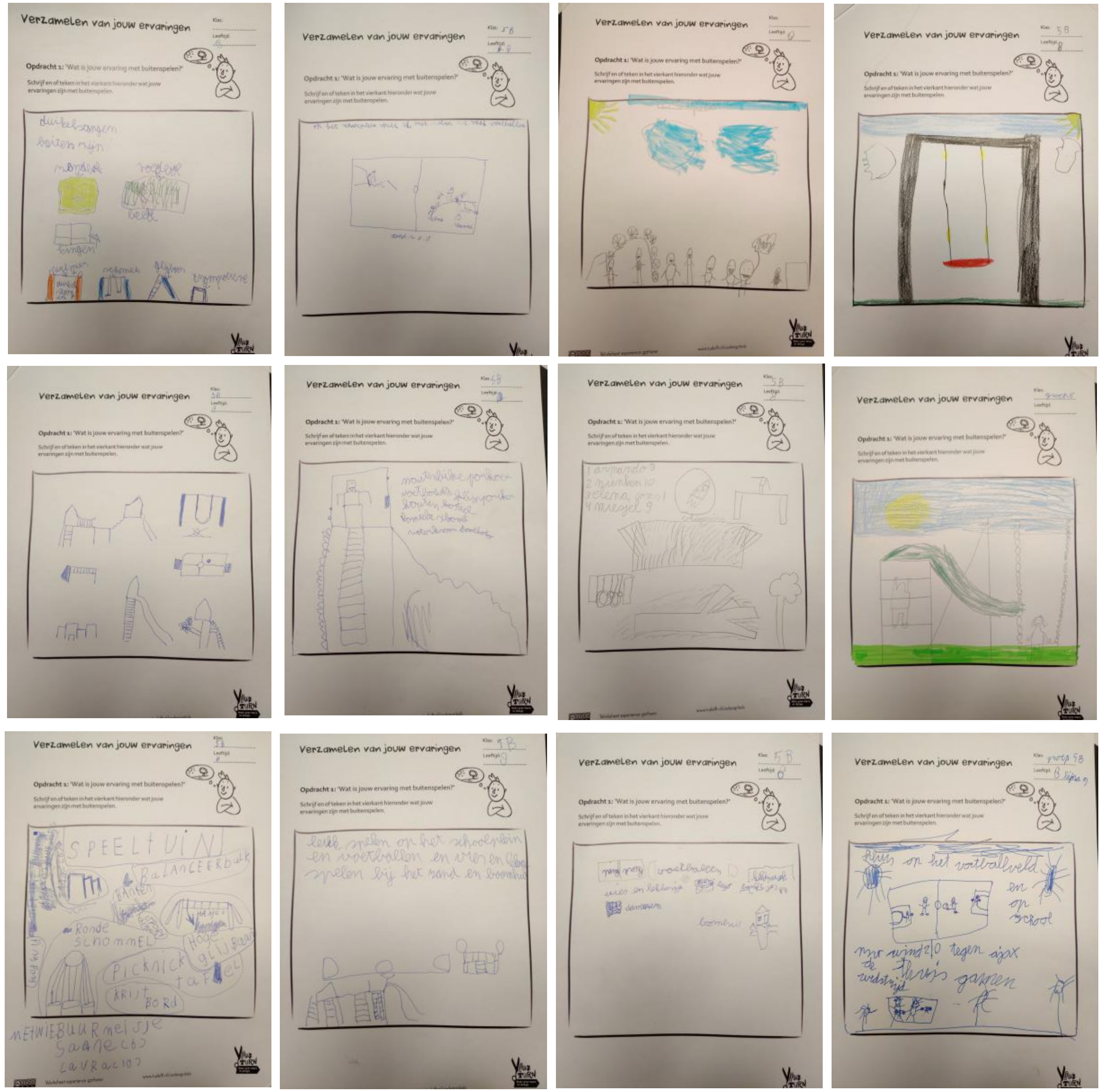








Session 1 | Experience gatherer

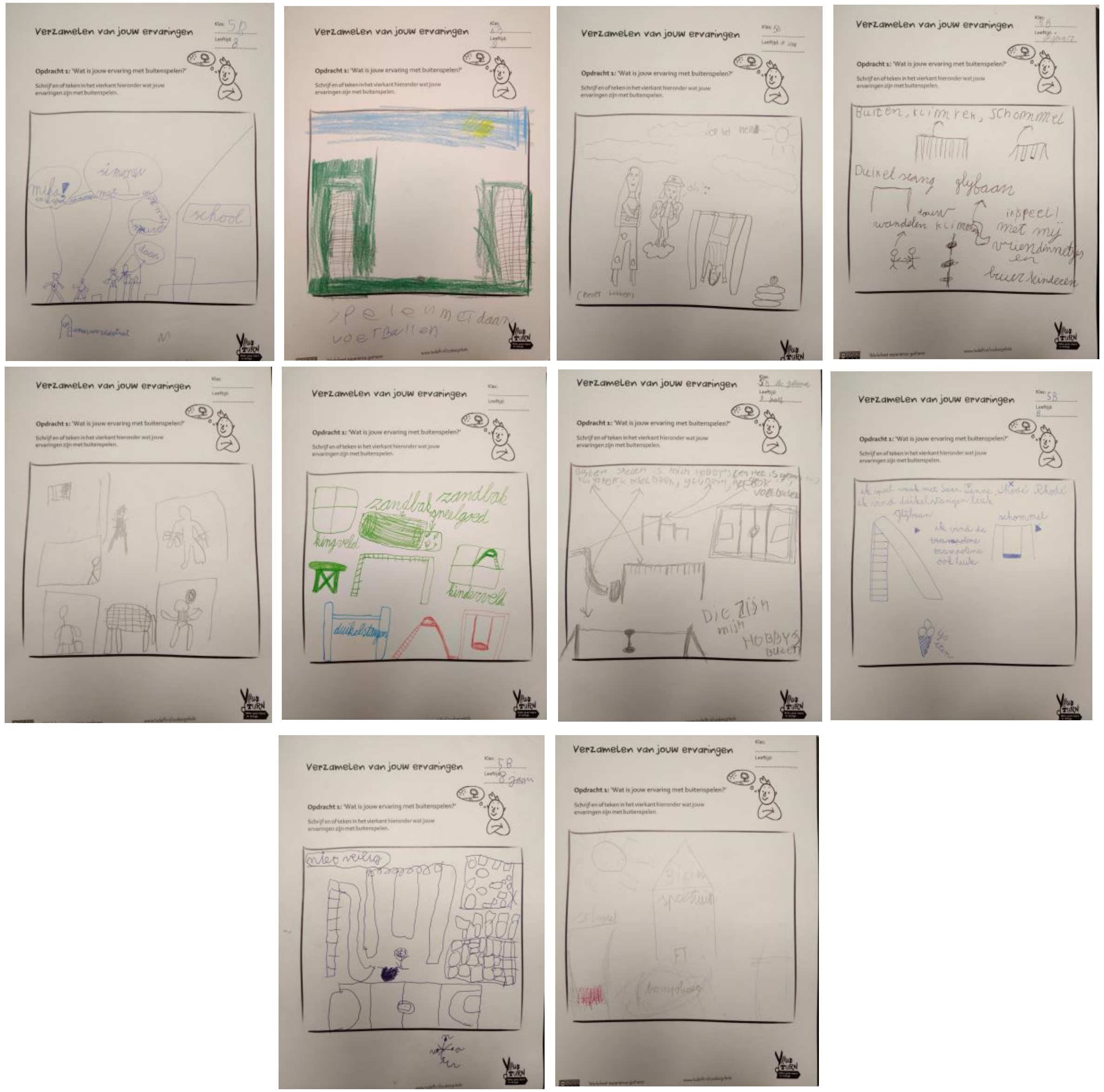
Class 5B Age 8-9 | Context mapping session 2 | Experience gatherer

Session 2 | Experience gatherer



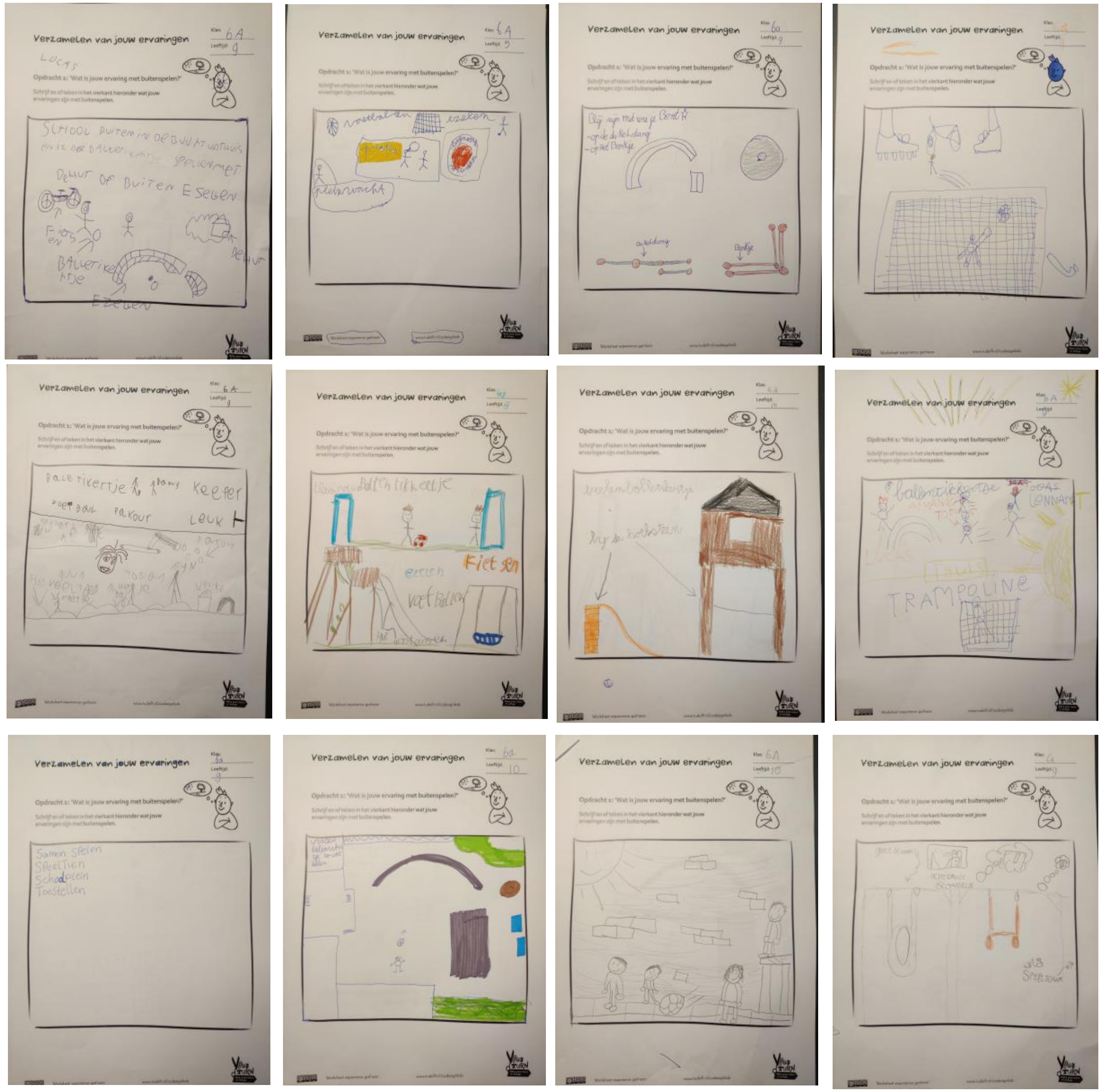
Class 5B Age 8-9 | Context mapping session 2 | Experience gatherer

Session 2 | Experience gatherer



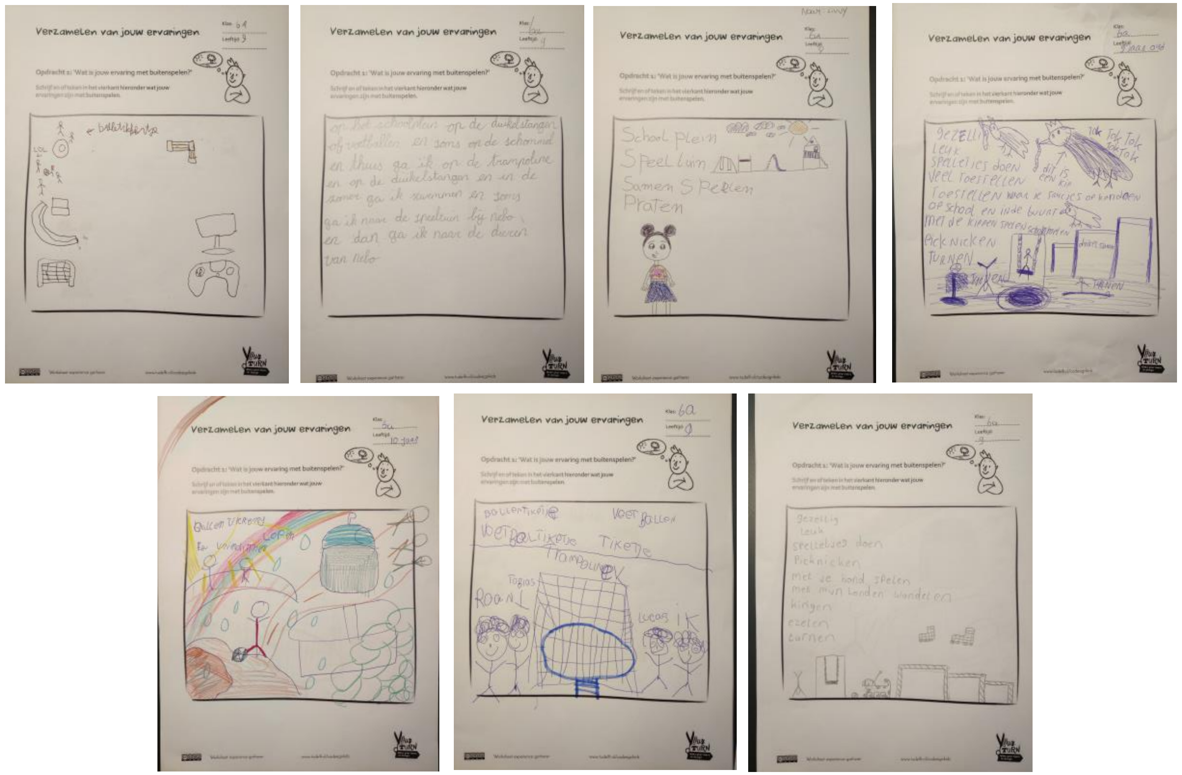
Class 6A Age 9-10 | Context mapping session 3 | Experience gatherer

Session 3 | Experience gatherer

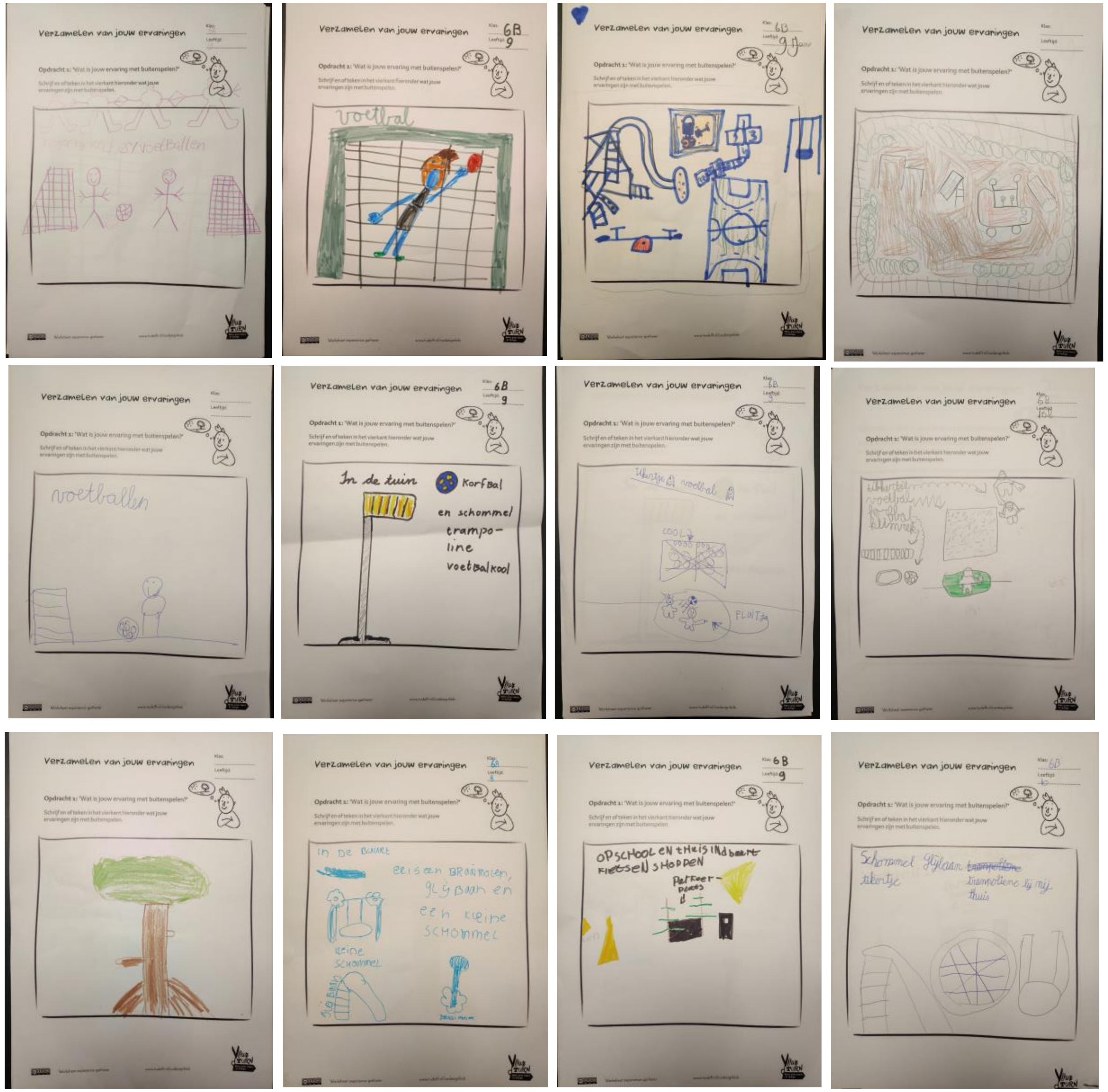


Class 6A Age 9-10 | Context mapping session 3 | Experience gatherer

Session 3 | Experience gatherer

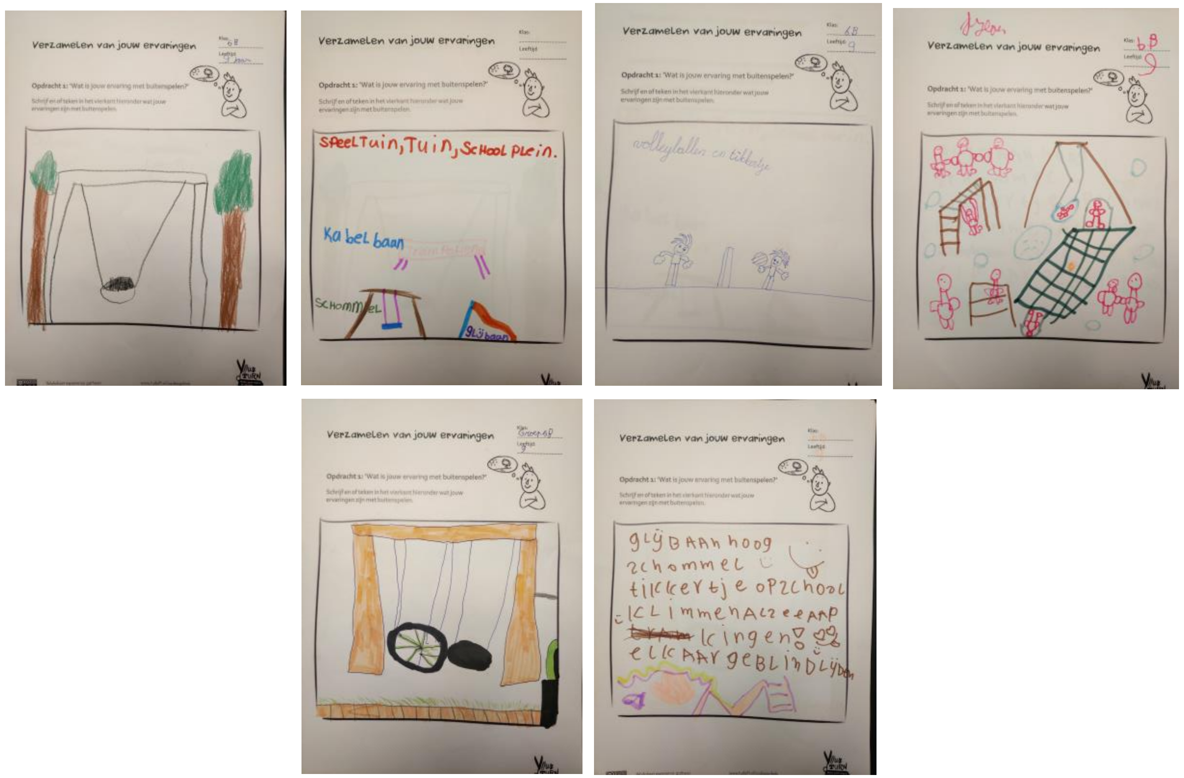


Session 4 | Experience gatherer



Appendix H
Class 6B Age 9-10 | Context mapping session 4 | Experience gatherer

Session 4 | Experience gatherer



Context mapping session | Experience gatherer clusters

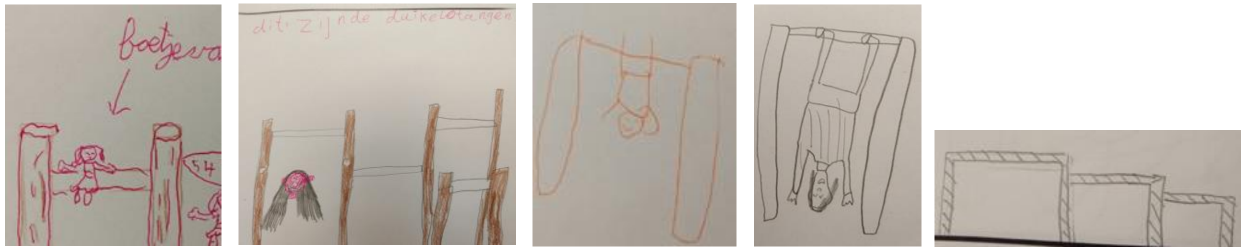
Playing soccer

Appendix H

Context mapping session | Experience gatherer clusters

Playing on the trampoline (jumping)

Using the tumble bars (tumbling)



Climbing

Range of different playground equipment

Appendix H

Context mapping session | Experience gatherer clusters

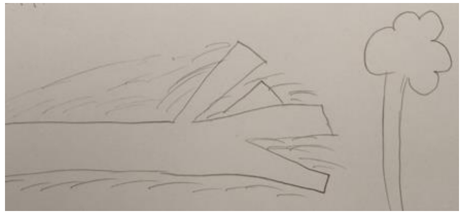
Swinging

Slides (sliding)

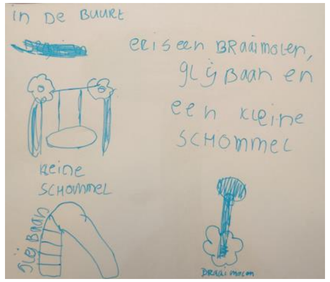
Playing on the school playground

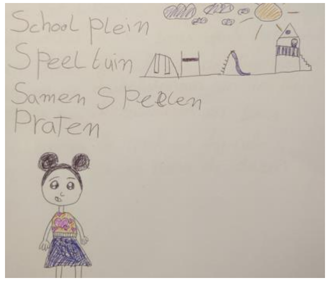
Nature/ trees



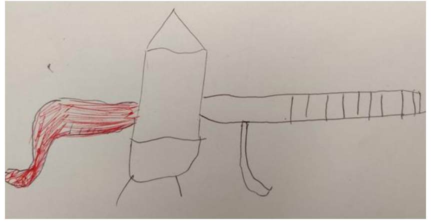
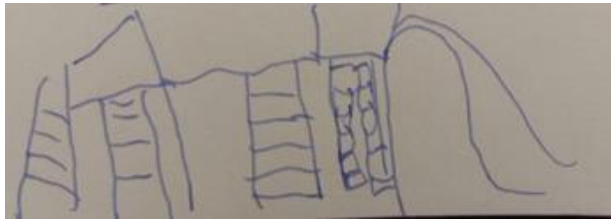


Playing in neighborhood playground

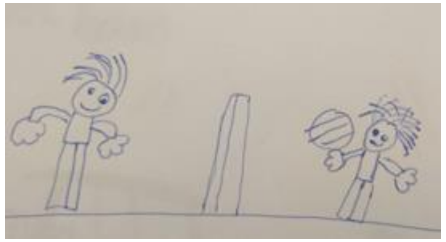



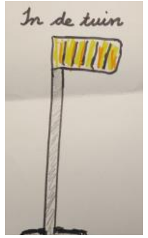


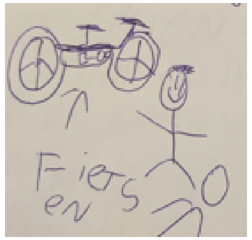
Playing on climbing castle

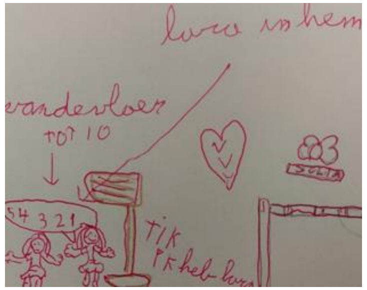
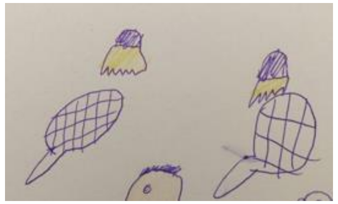
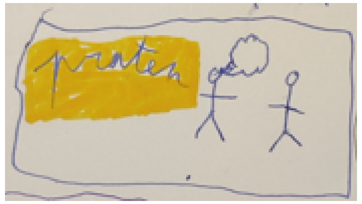



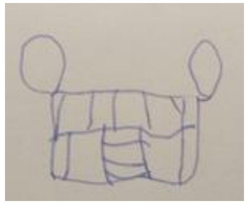

Other activities





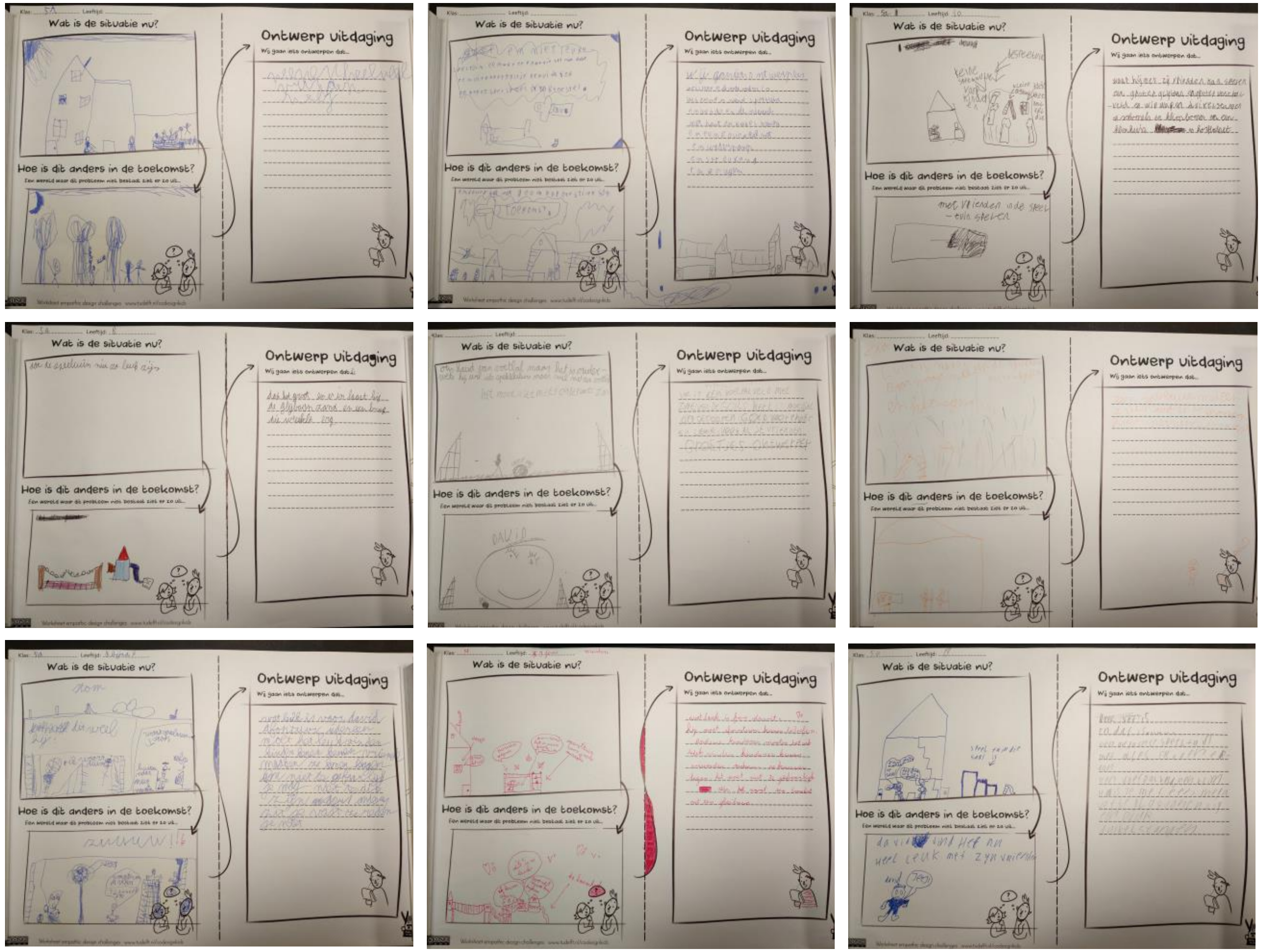




Class 5A Age 8-9 | Context mapping session 1 | Emphatic design challenge

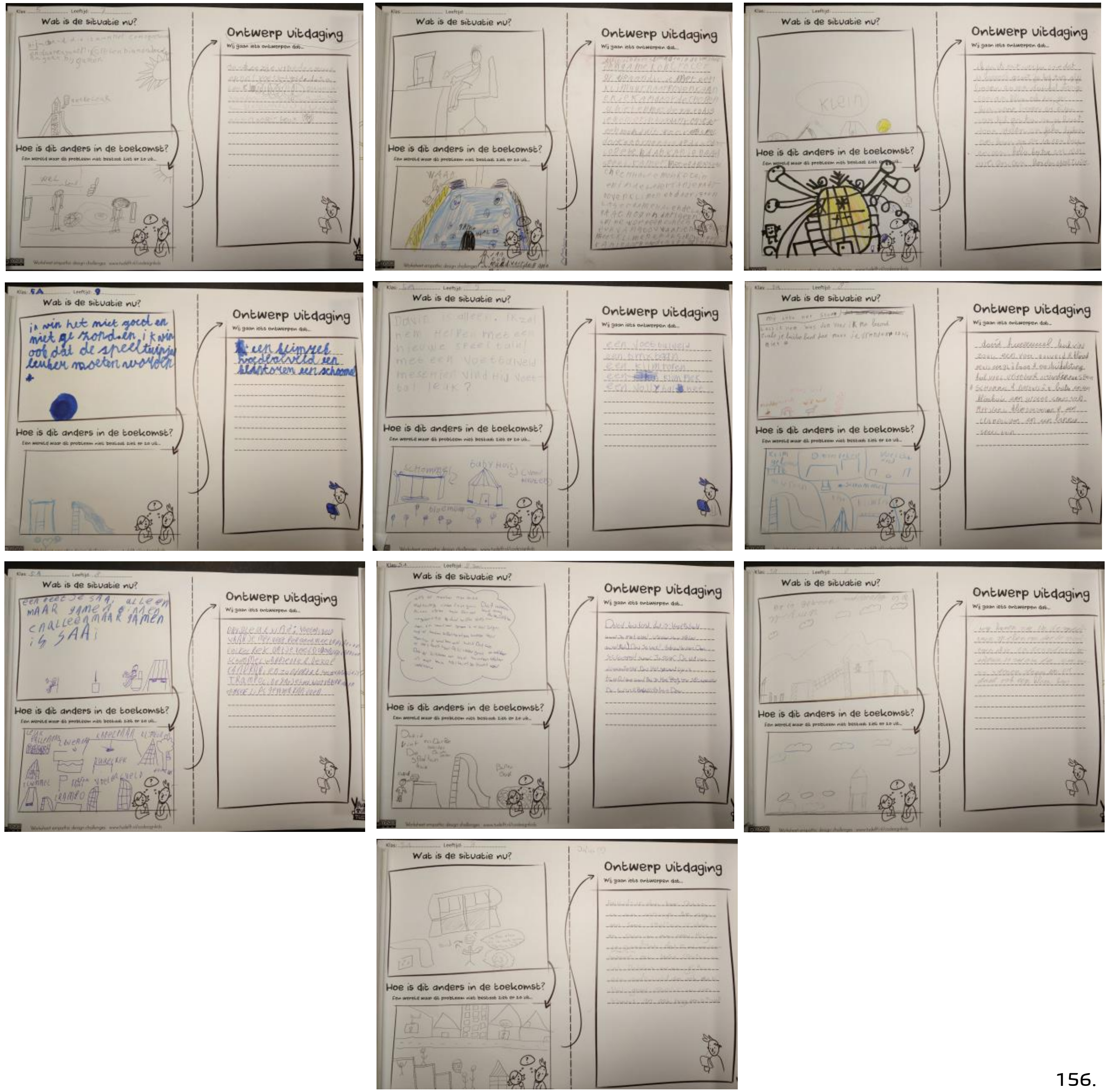
Session 1 | Emphatic design challenge



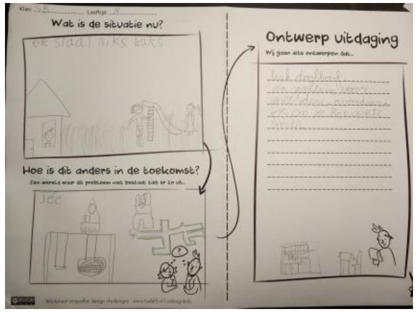
Appendix I

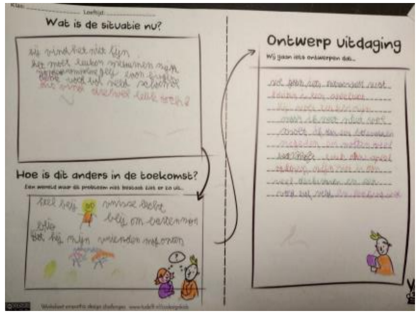
Class 5A Age 8-9 | Context mapping session 1 | Emphatic design challenge

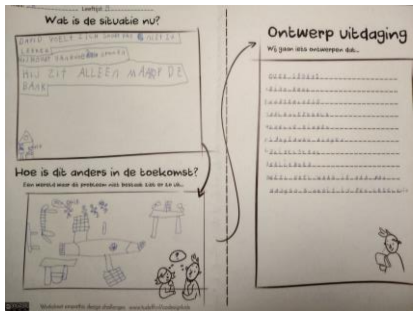
Session 1 | Emphatic design challenge

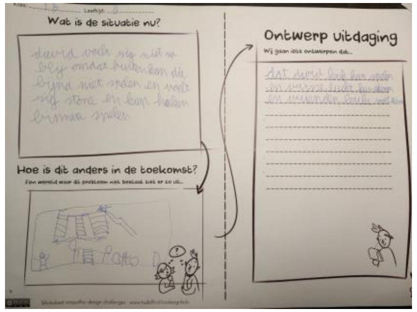


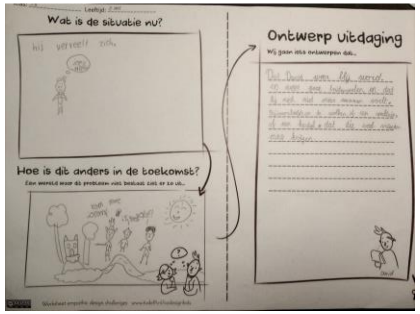
Session 2 | Emphatic design challenge

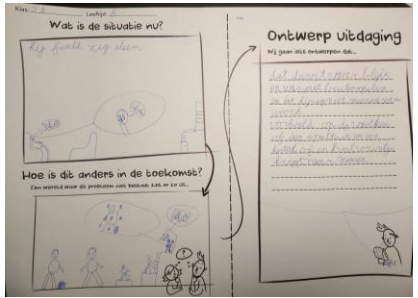


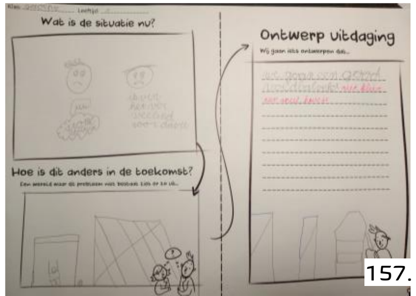




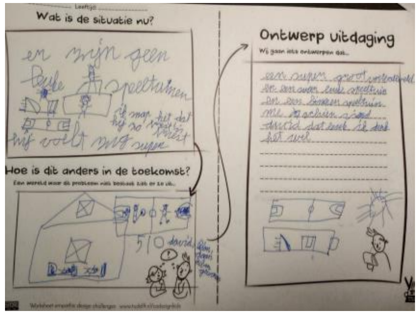


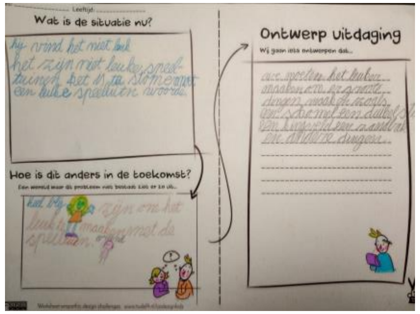


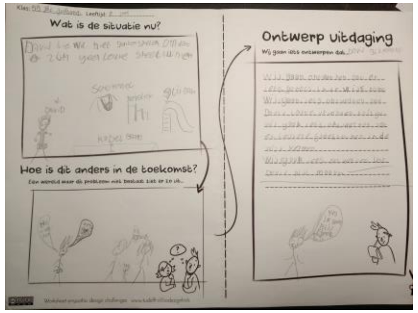


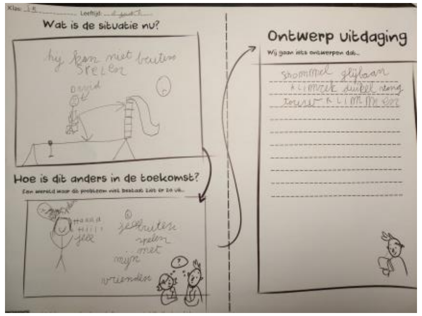


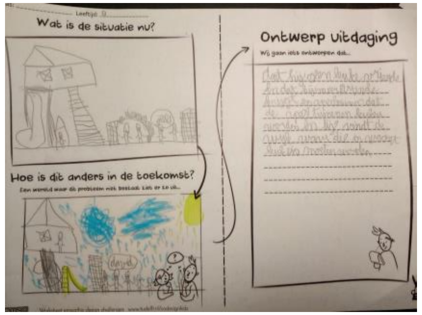
Session 2 | Emphatic design challenge

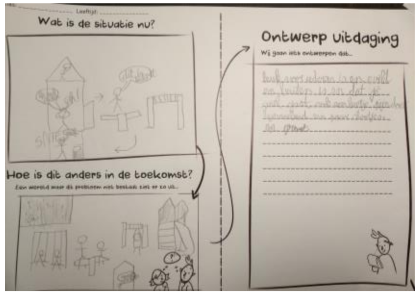


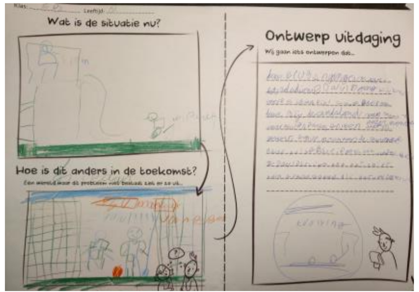








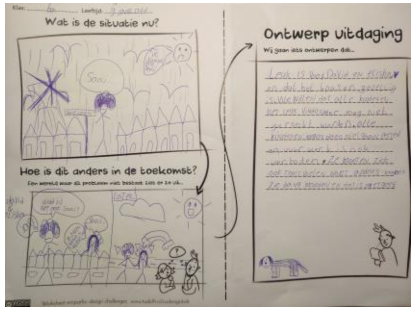
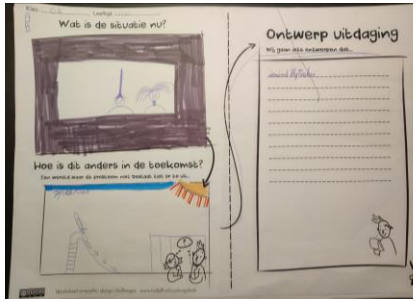


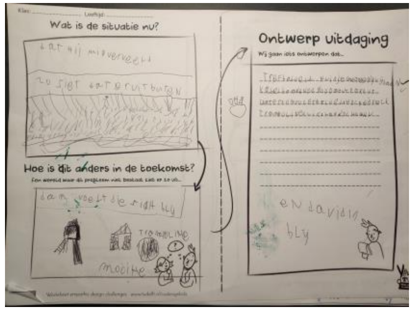
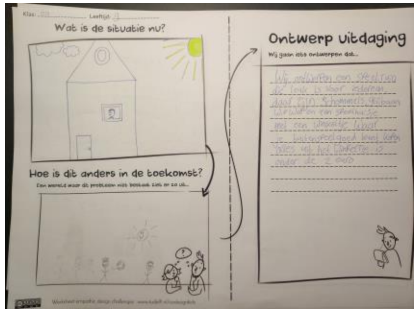


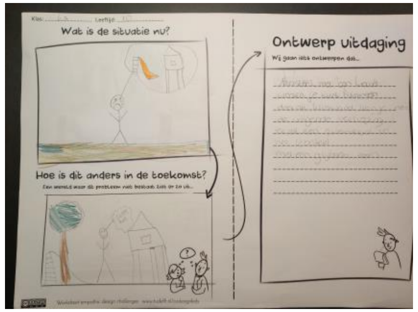
Class 6A Age 9-10 | Context mapping session 3 | Emphatic design challenge

Session 3 | Emphatic design challenge



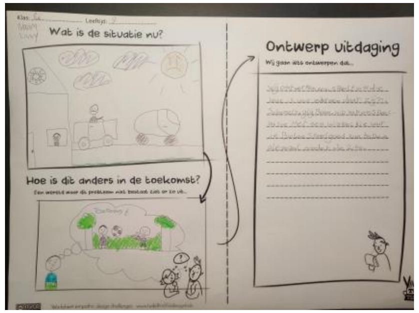



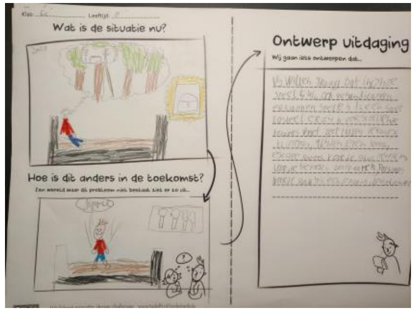
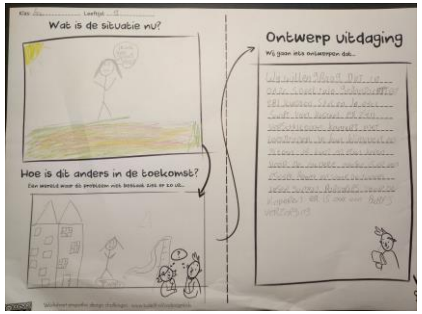



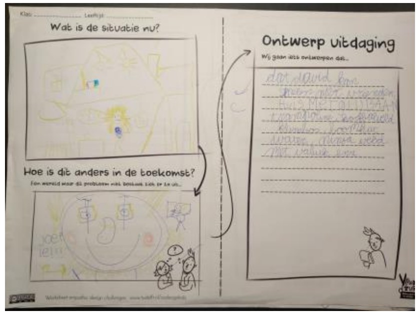
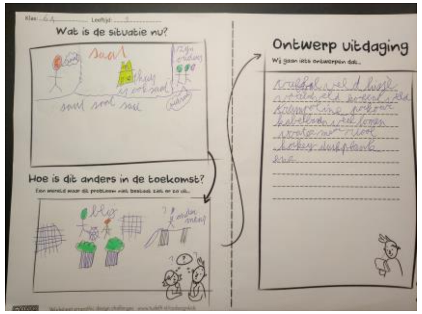
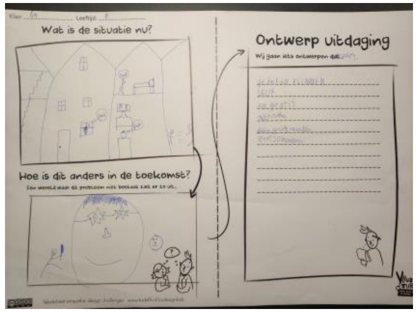
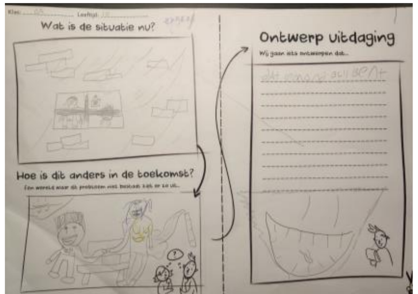


Class 6A Age 9-10 | Context mapping session 3 | Emphatic design challenge

Session 3 | Emphatic design challenge

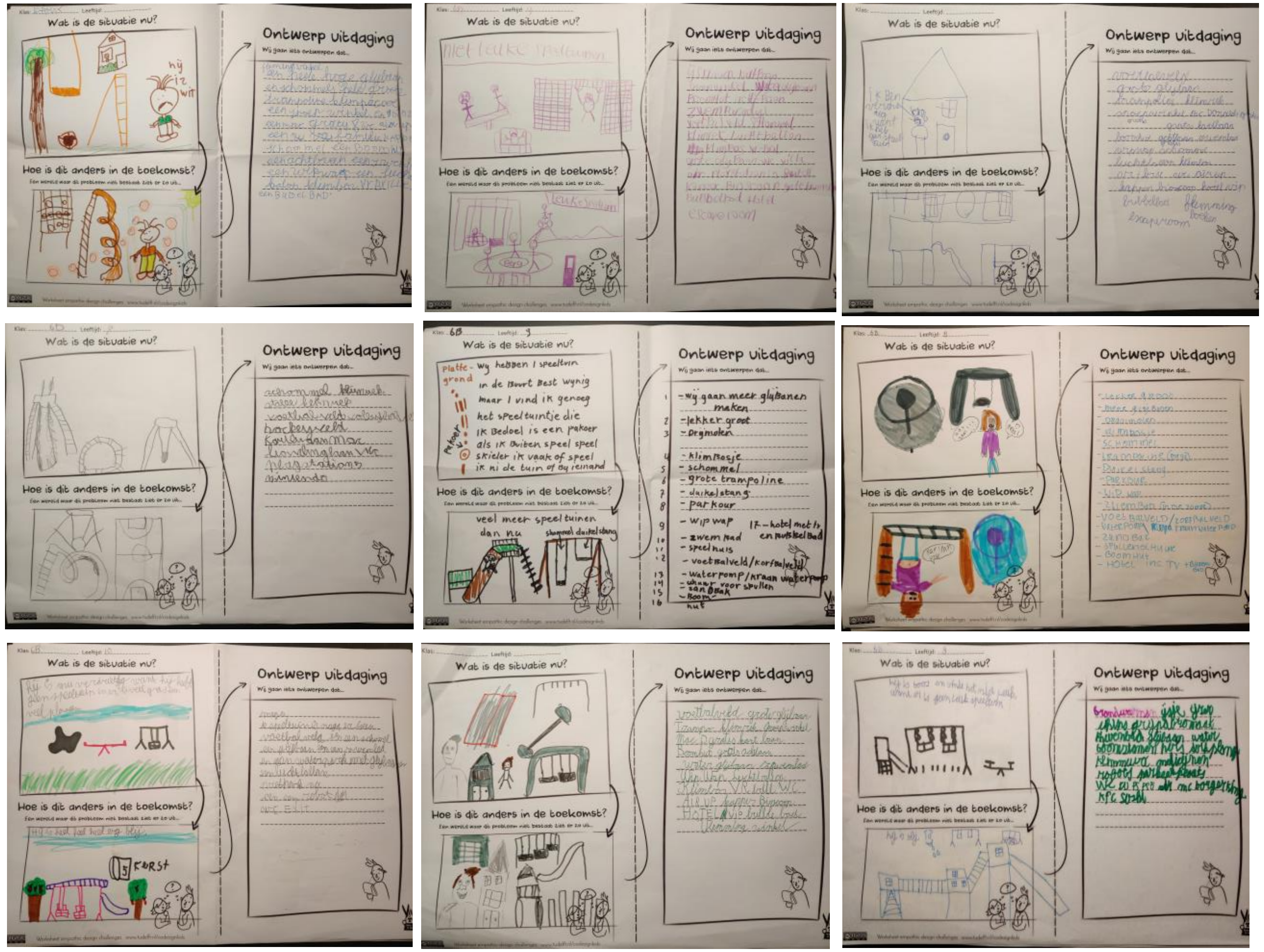



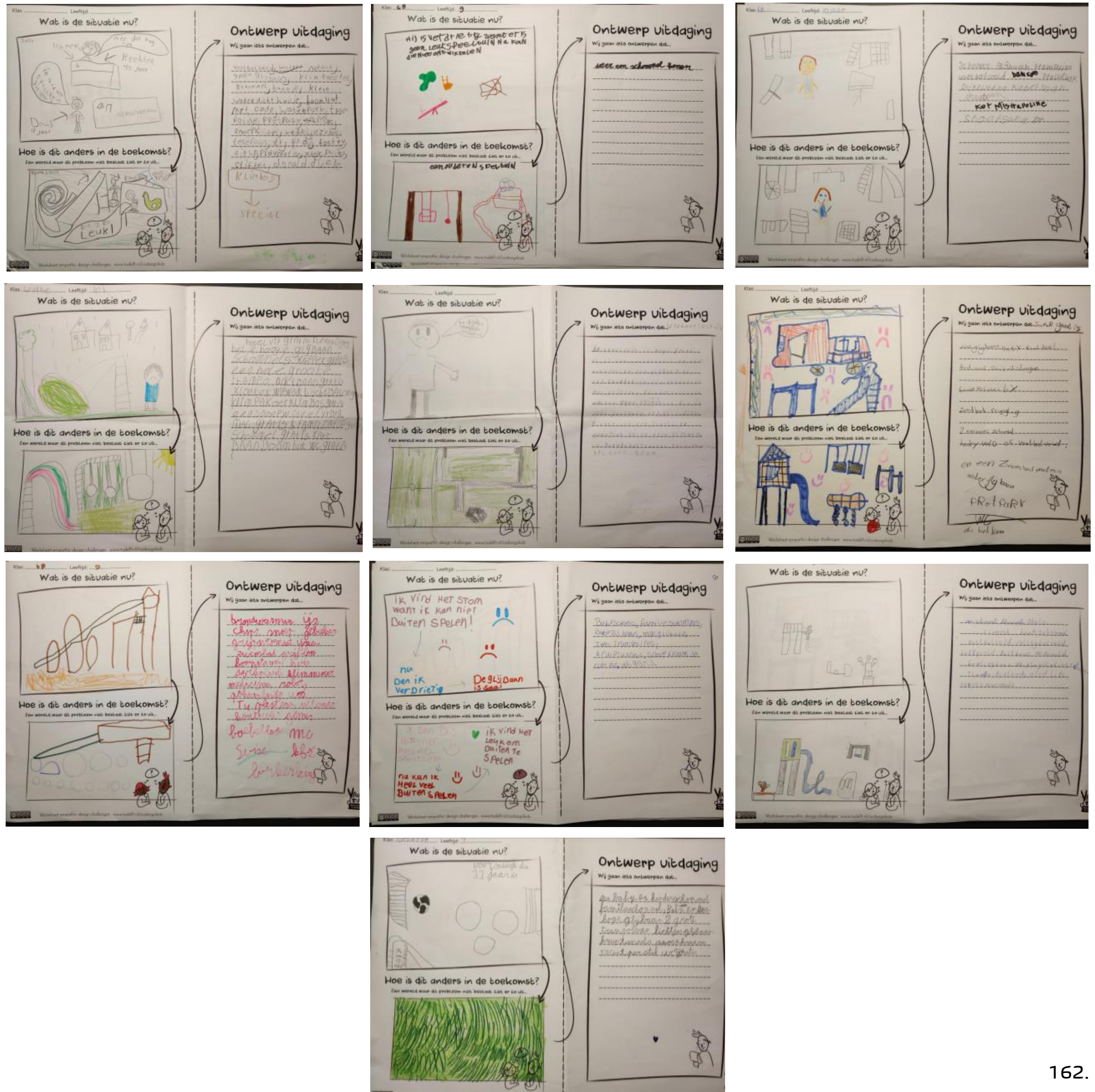
Class 6B Age 9-10 | Context mapping session 4 | Emphatic design challenge

Session 4 | Emphatic design challenge



Class 6B Age 9-10 | Context mapping session 4 | Emphatic design challenge

Session 4 | Emphatic design challenge



Appendix J

Class 5A Age 8-9 | Design session 1 | Idea brainstorm + dot voting technique

Session 1 | Idea brainstorm + dot voting technique

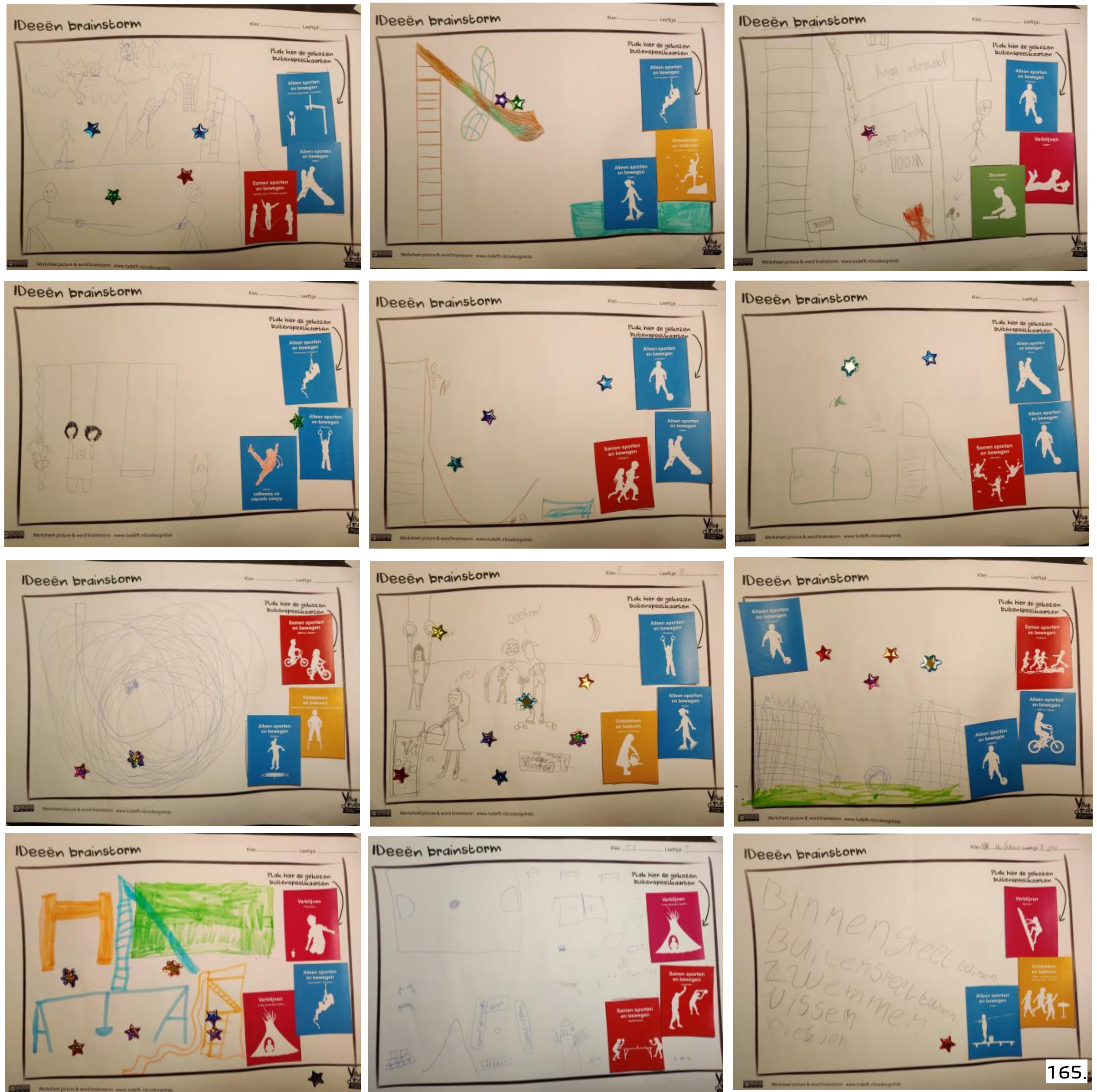
Appendix J

Class 5A Age 8-9 | Design session 1 | Idea brainstorm + dot voting technique

Session 1 | Idea brainstorm + dot voting technique

Class 5B Age 8-9 | Design session 2 | Idea brainstorm + dot voting technique

Session 2 | Idea brainstorm + dot voting technique

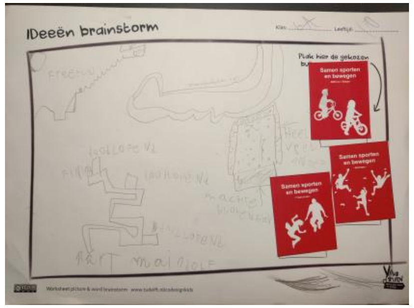


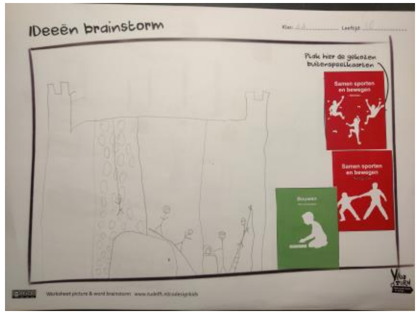
Class 5B Age 8-9 | Design session 2 | Idea brainstorm + dot voting technique

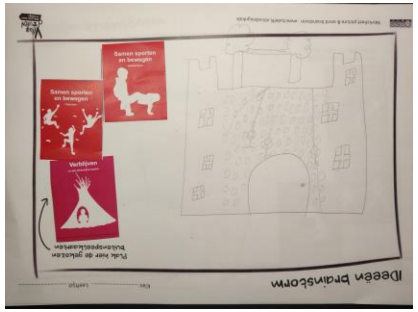
Session 2 | Idea brainstorm + dot voting technique

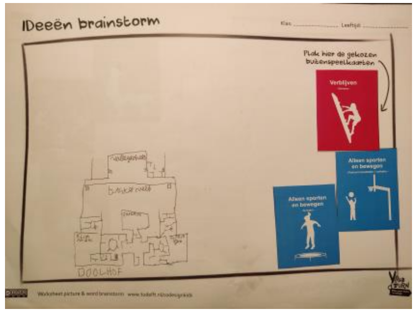
Class 6A Age 9-10 | Design session 3 | Idea brainstorm + dot voting technique

Session 3 | Idea brainstorm + dot voting technique



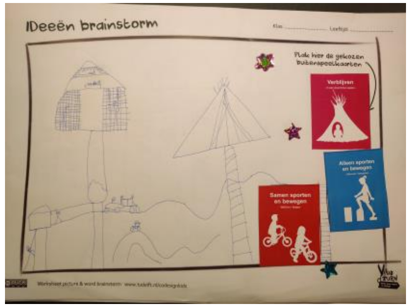


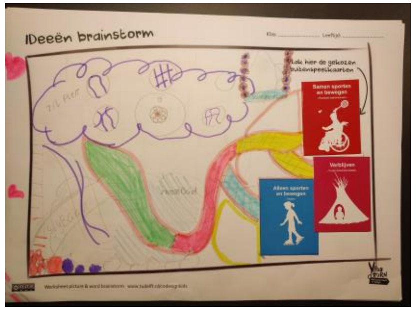


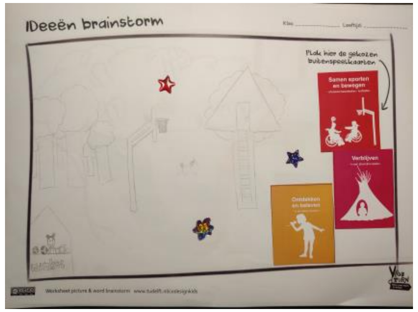


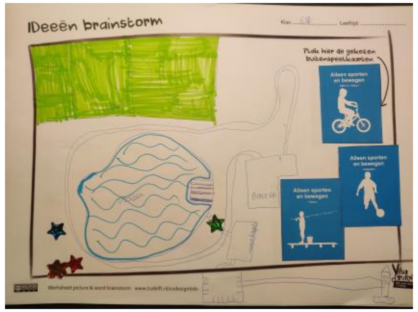
Class 6A Age 9-10 | Design session 3 | Idea brainstorm + dot voting technique

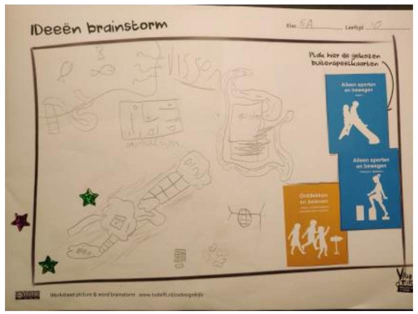
Session 3 | Idea brainstorm + dot voting technique

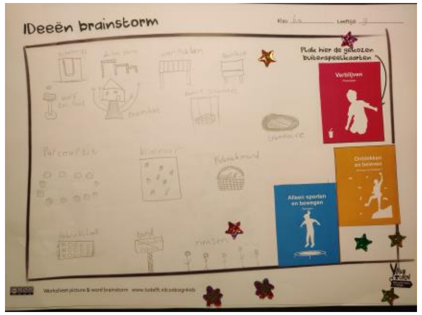








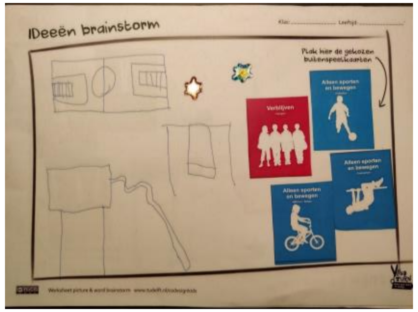


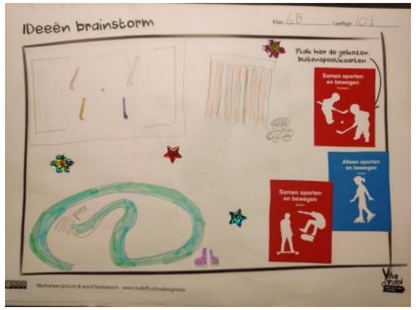


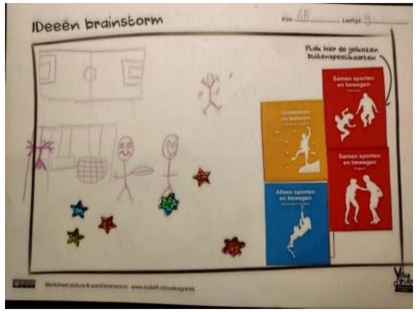
Appendix J

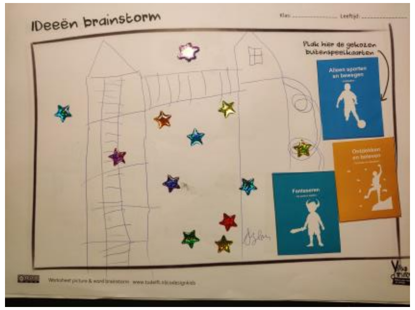
Class 6B Age 9-10 | Design session 4 | Idea brainstorm + dot voting technique

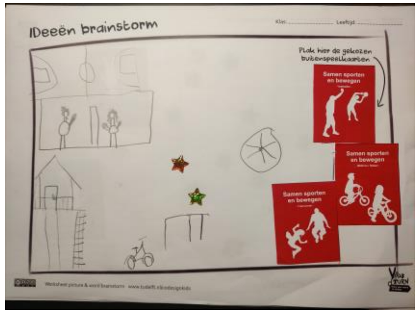
Session 4 | Idea brainstorm + dot voting technique

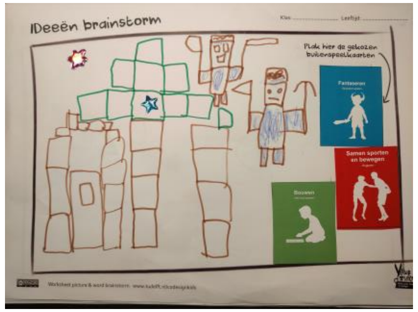








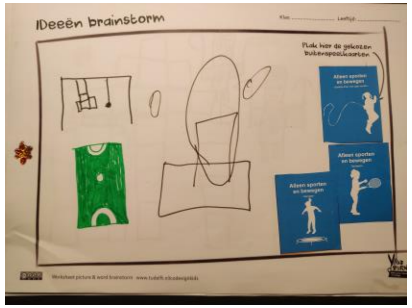


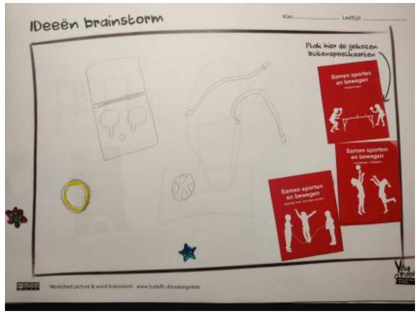


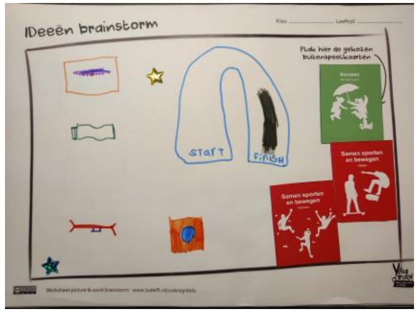
Appendix J

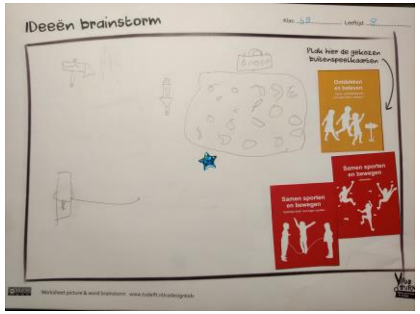
Class 6B Age 9-10 | Design session 4 | Idea brainstorm + dot voting technique

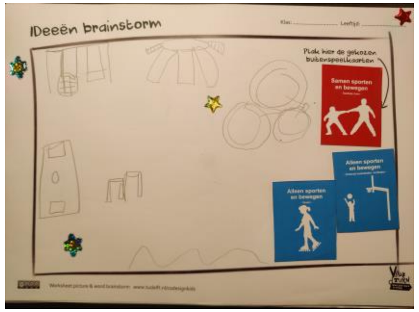
Session 4 | Idea brainstorm + dot voting technique

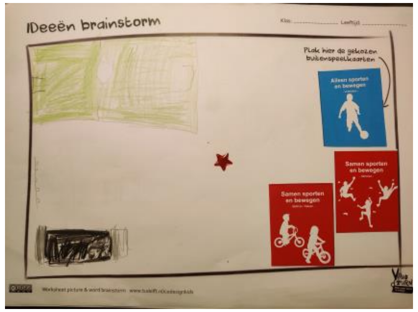


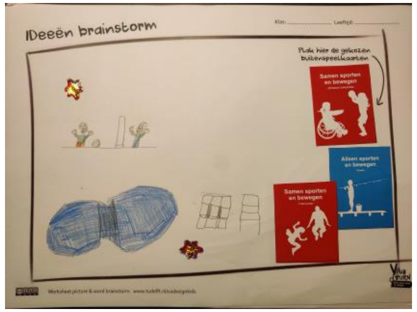


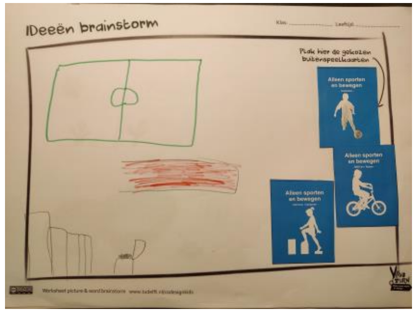


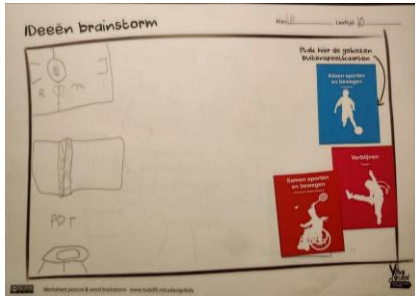




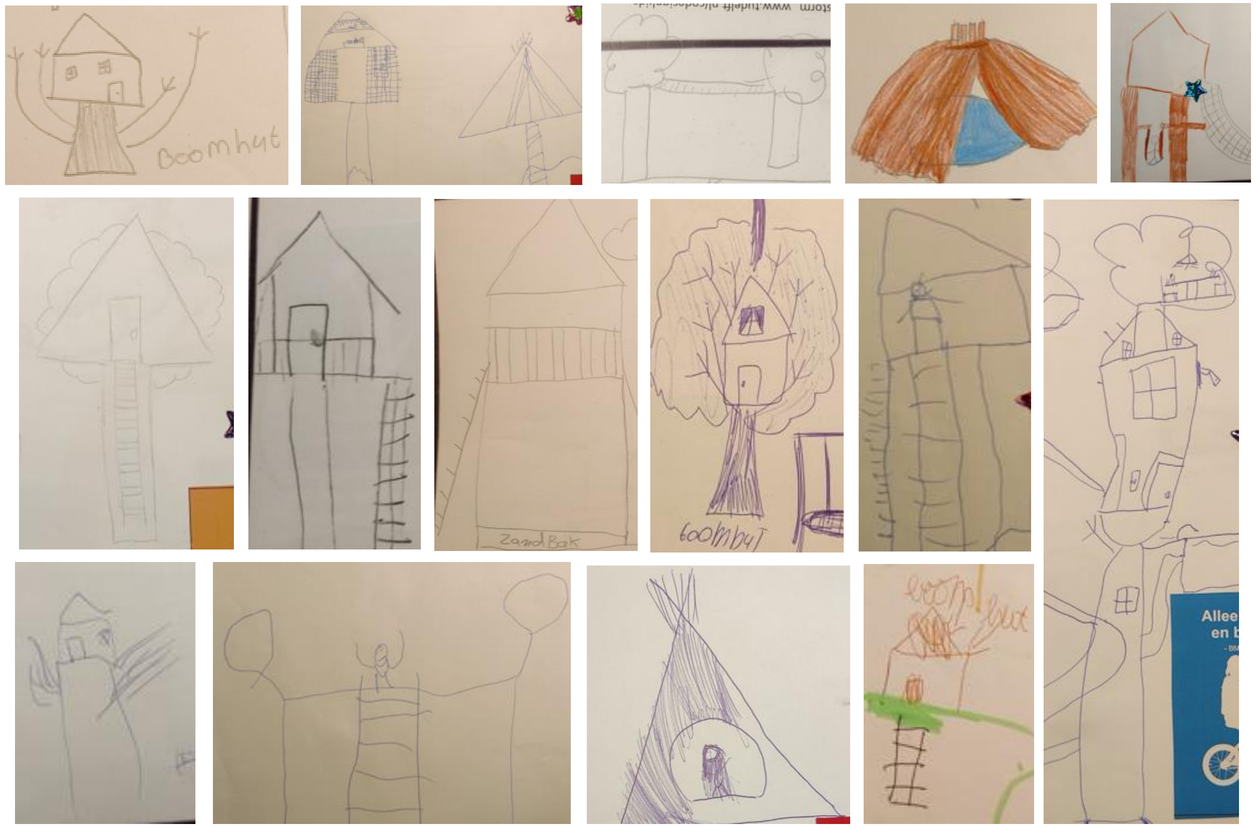








Treehouse/ hut



Soccer field

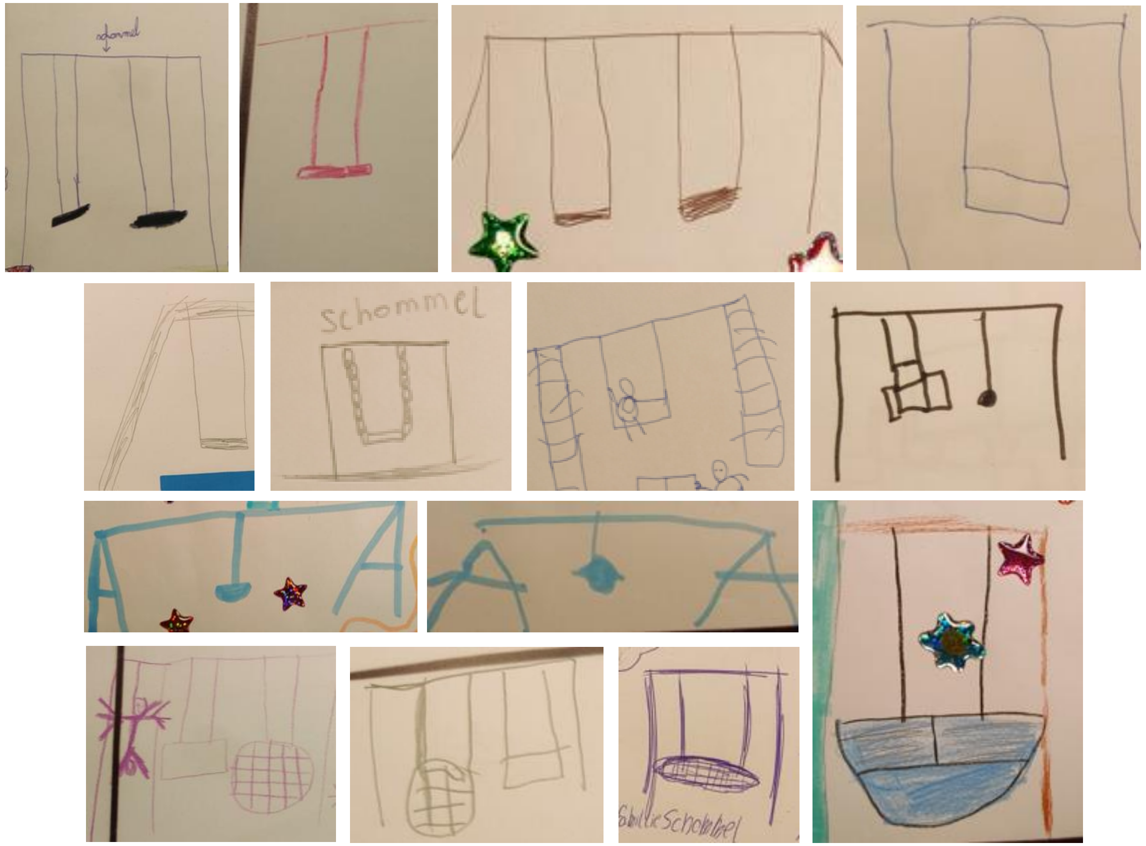
Design session | Idea brainstorm clusters

Climbing structures

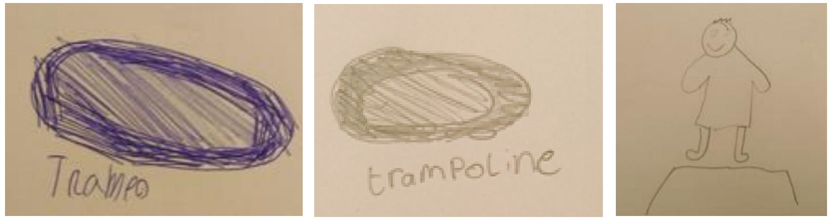
Appendix J

Design session | Idea brainstorm clusters

Swings



Trampoline



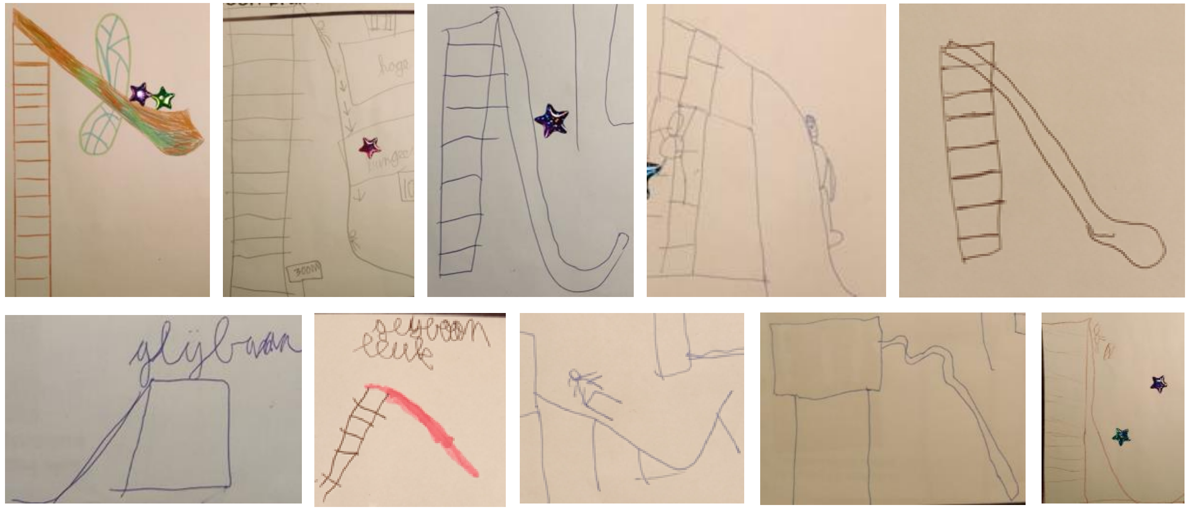
BMX track

Skate park

Appendix J

Design session | Idea brainstorm clusters

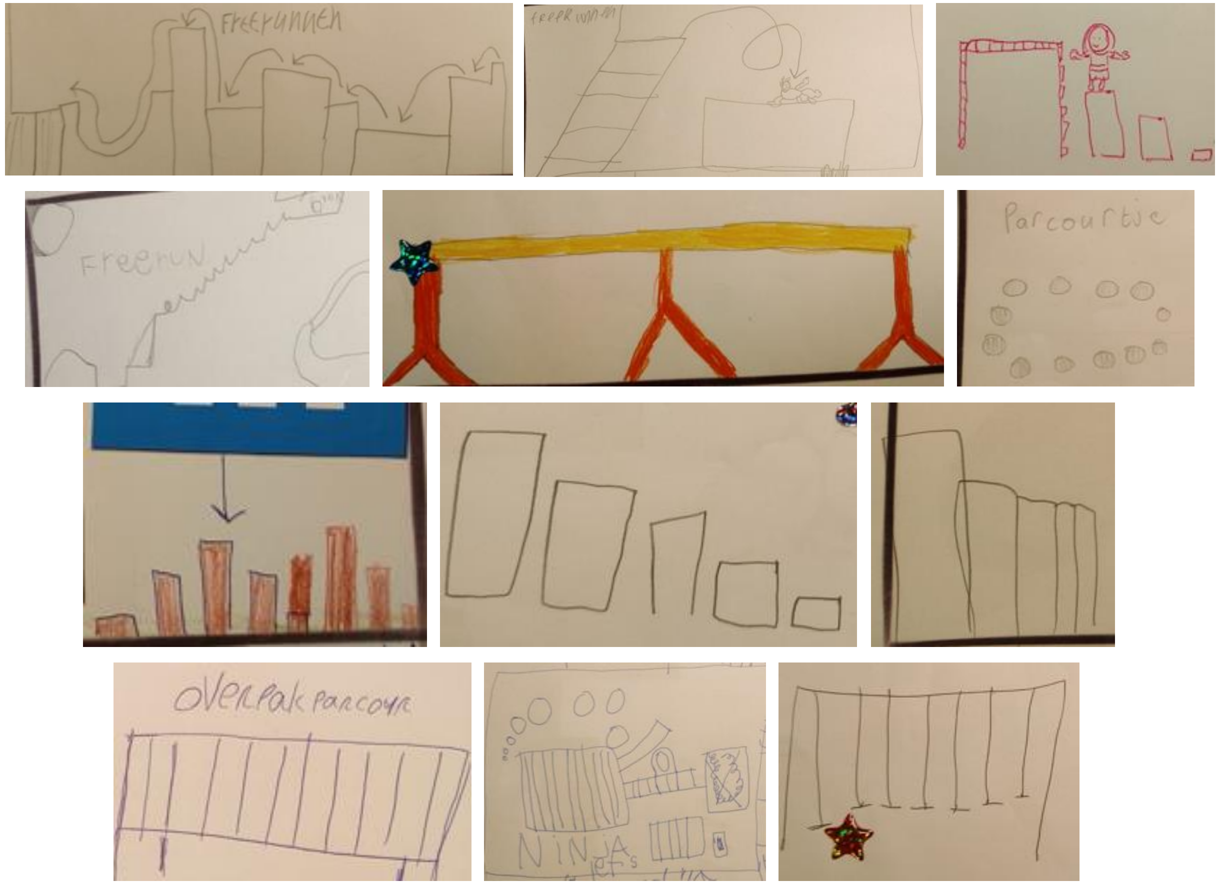
Slides



Gymnastics rings (fitness)

Tumble bars

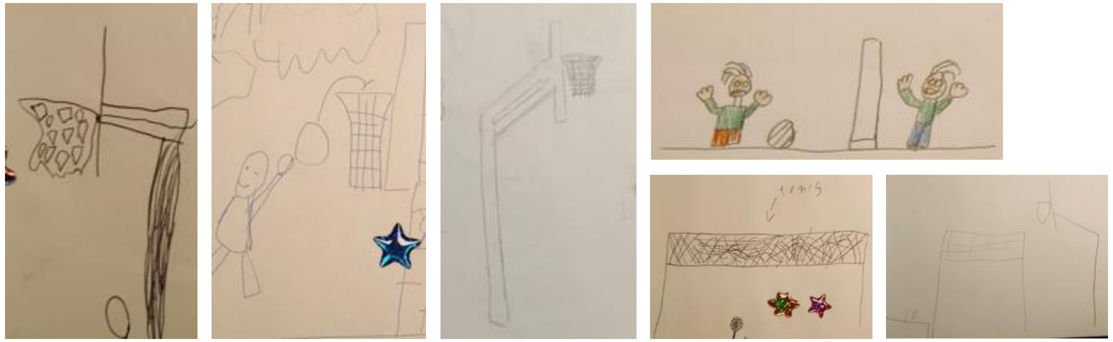
Free running parkour



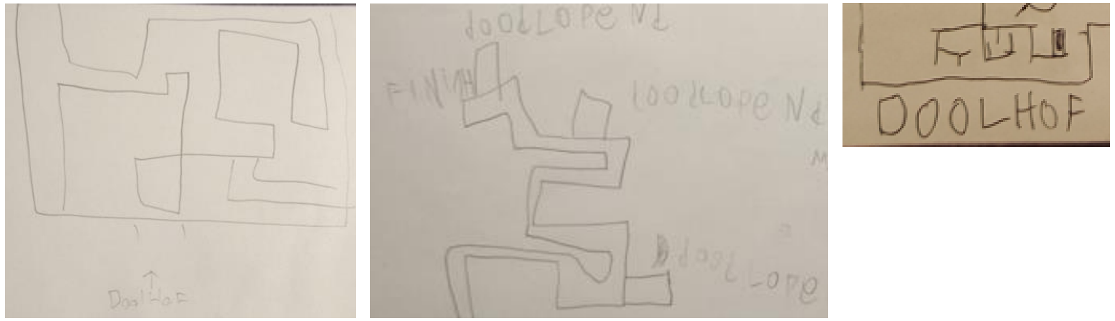
Appendix J

Design session | Idea brainstorm clusters

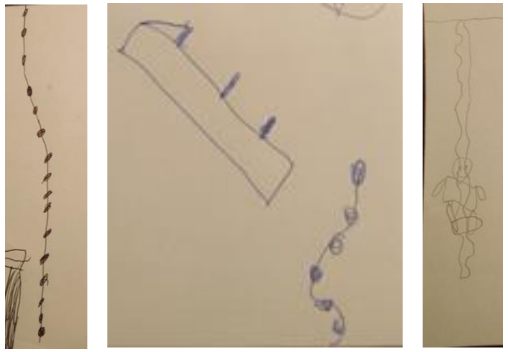
Ball sports



Maze

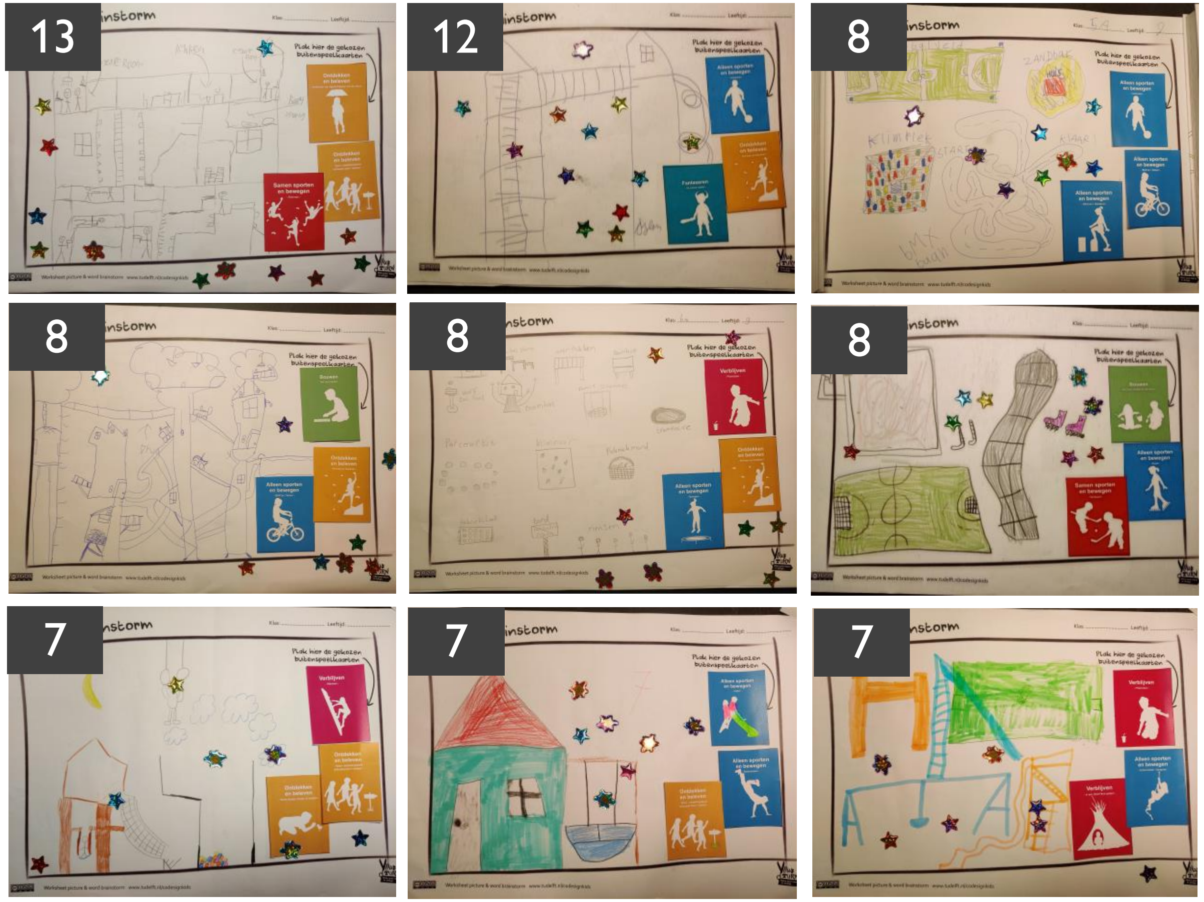


Rope climbing



Class 5A,5B,6A,6B Age 8-10 | Highest scores design session

Highest score (as rated by children)



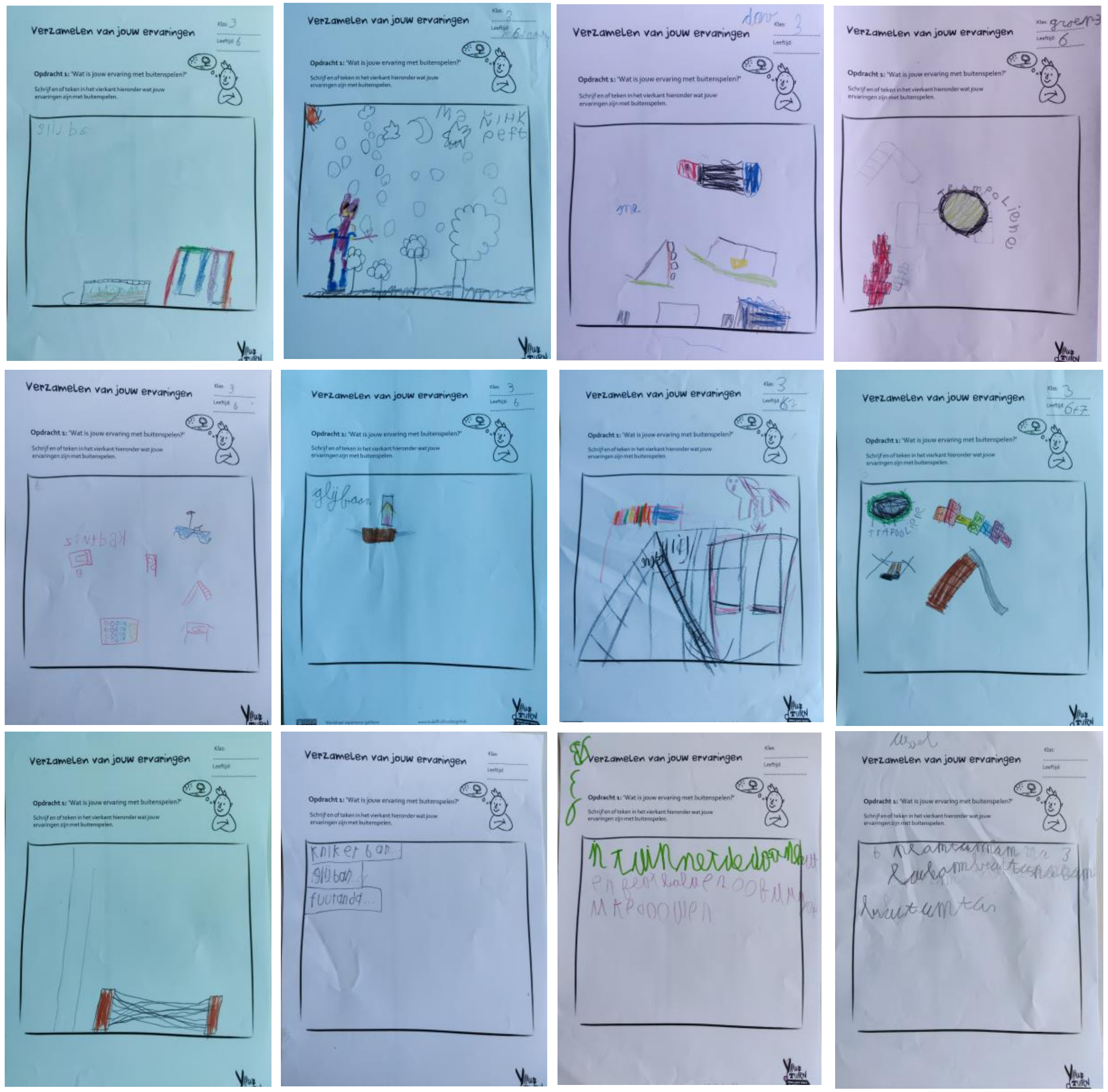
Appendix K

Class 5A,5B,6A,6B Age 8-10 | Highest scores design session

Highest score (as rated by children)

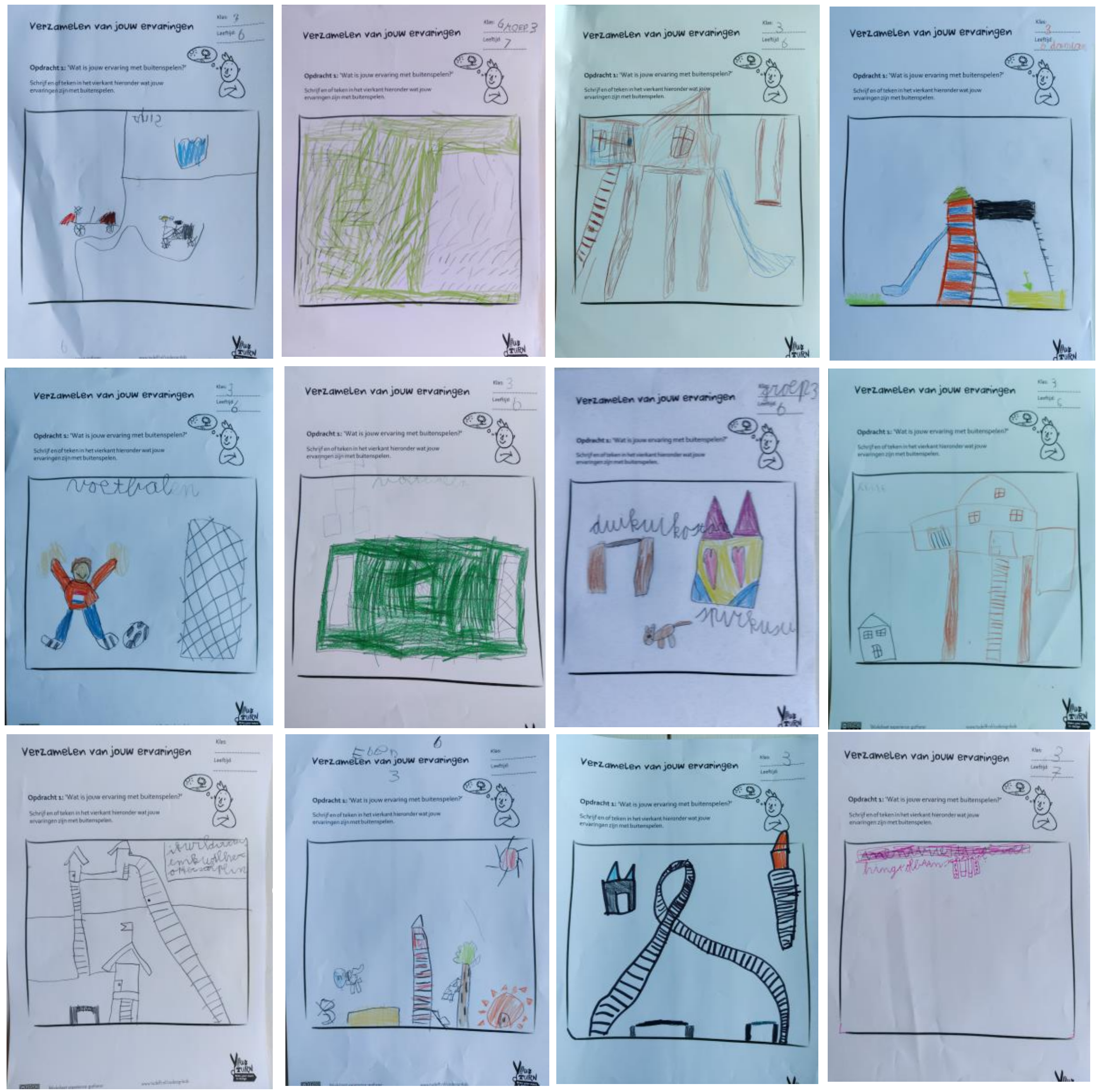
Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer

Session 5 | Experience gatherer



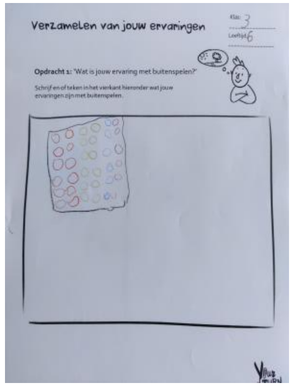
Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer

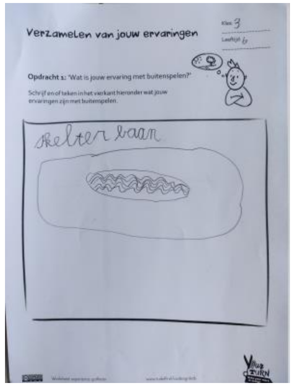
Session 5 | Experience gatherer

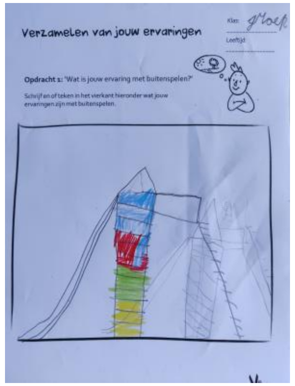


Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer

Session 5 | Experience gatherer

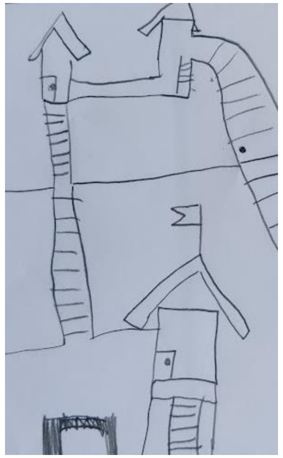


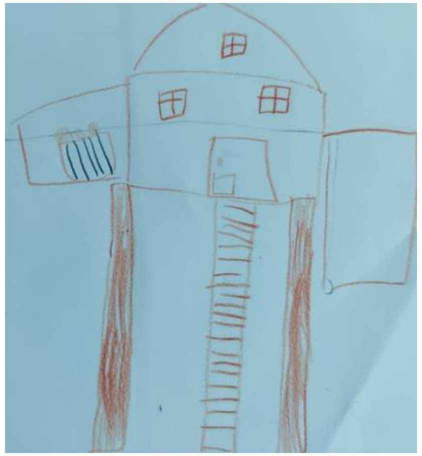




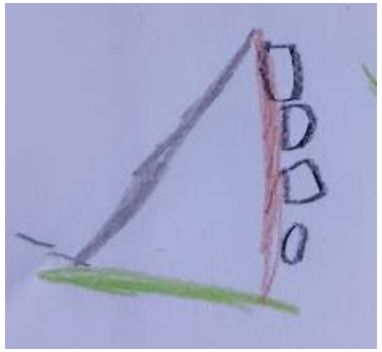
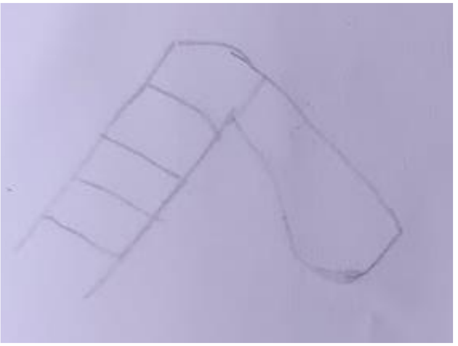
Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer clusters

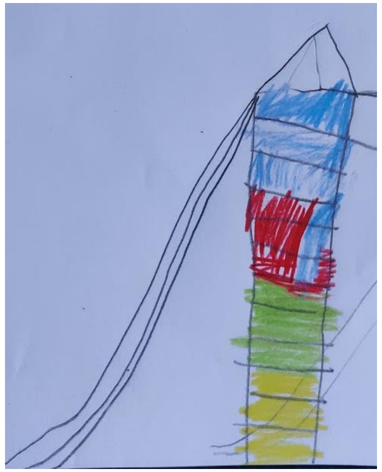
Climbing/ playing in treehouse

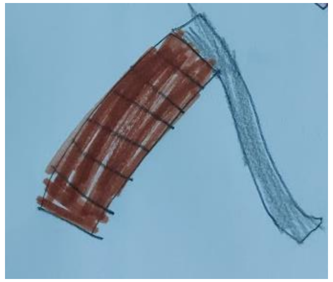
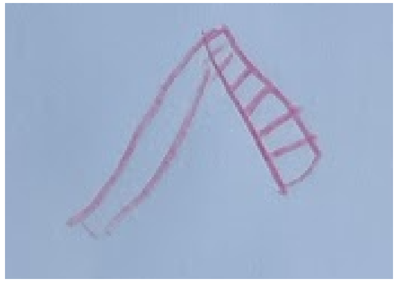




Sliding

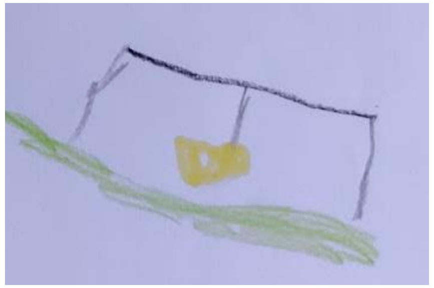


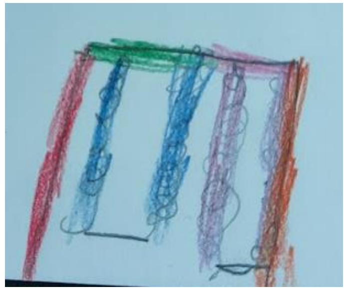




Appendix L

Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer clusters

Swinging





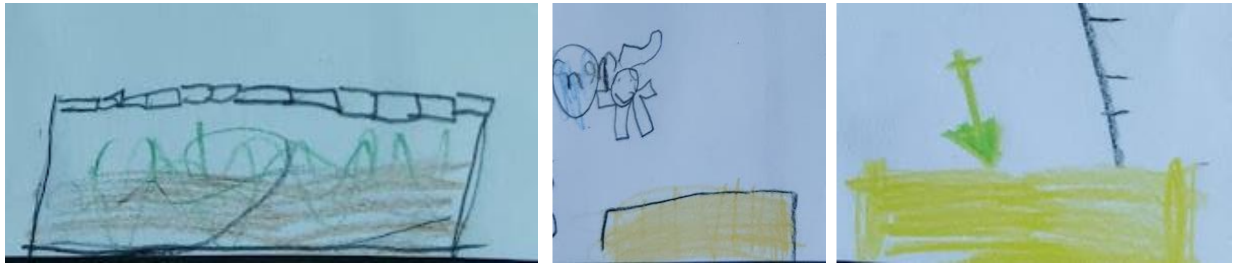

Jumping on trampoline



Appendix L

Class 3 Age 6-7 | Context mapping session 5 | Experience gatherer clusters

Playing in sandbox

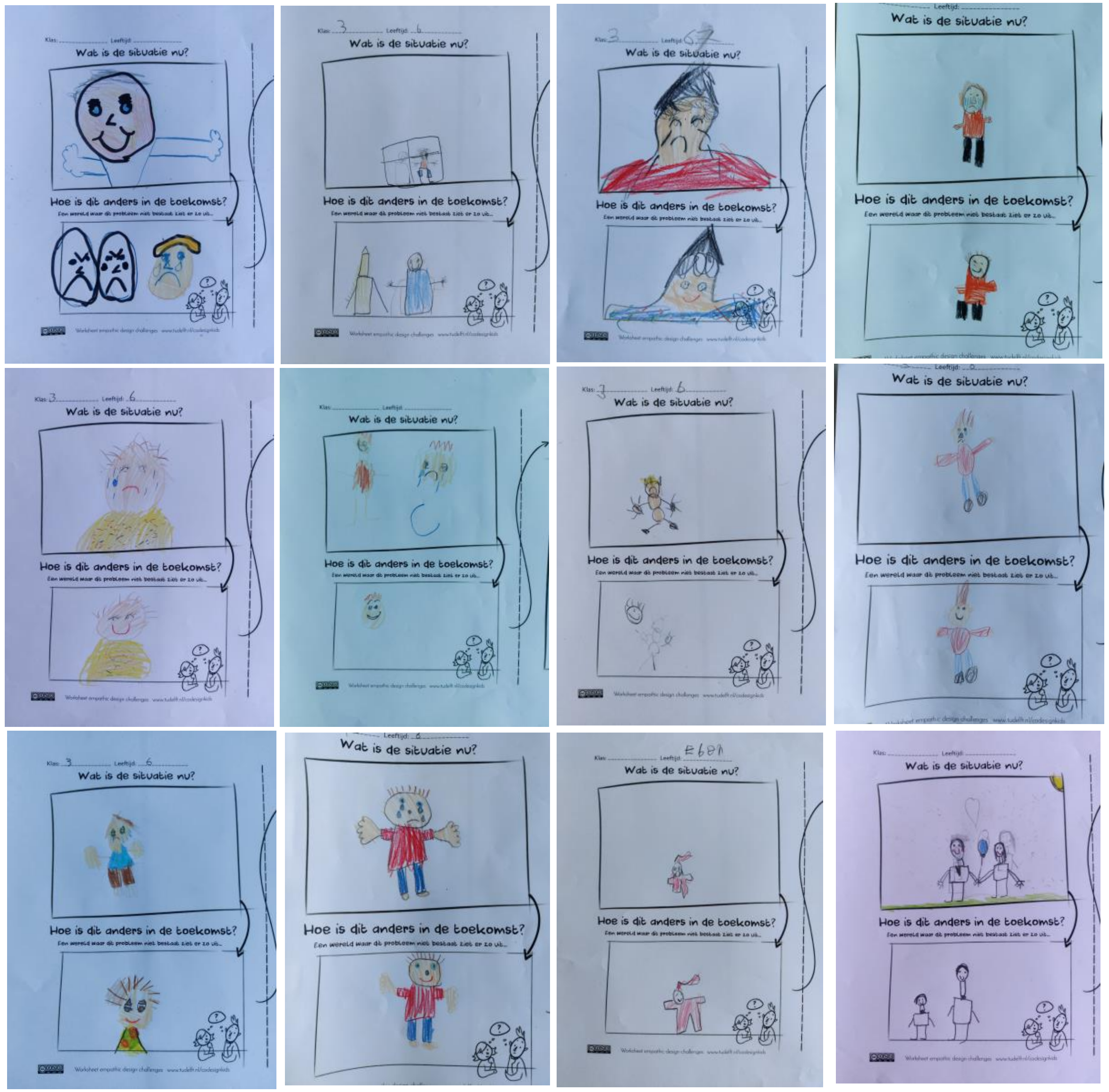


Playing soccer

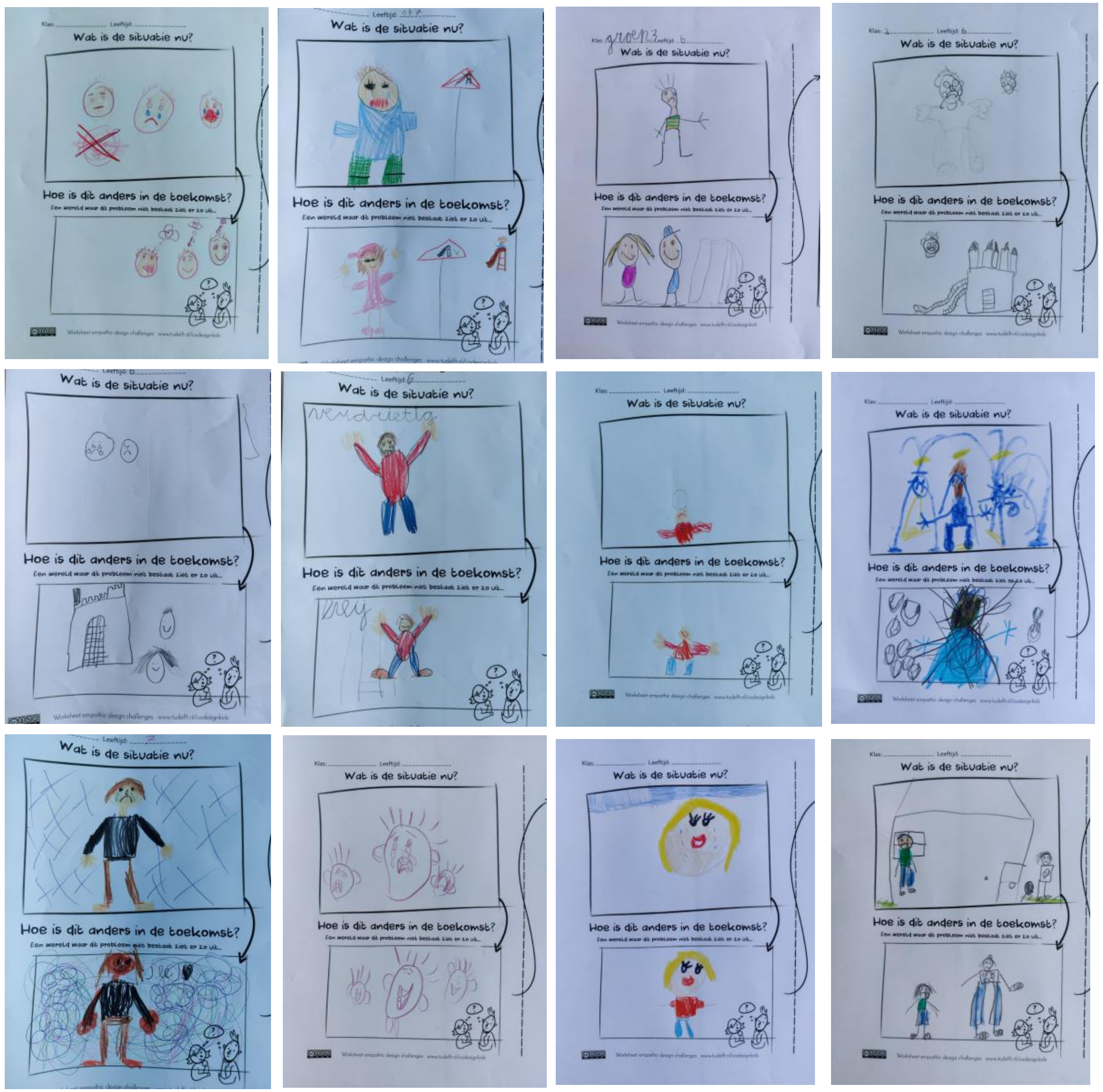
Appendix M

Class 3 Age 6-7 | Context mapping session 5 | Emphatic design challenge

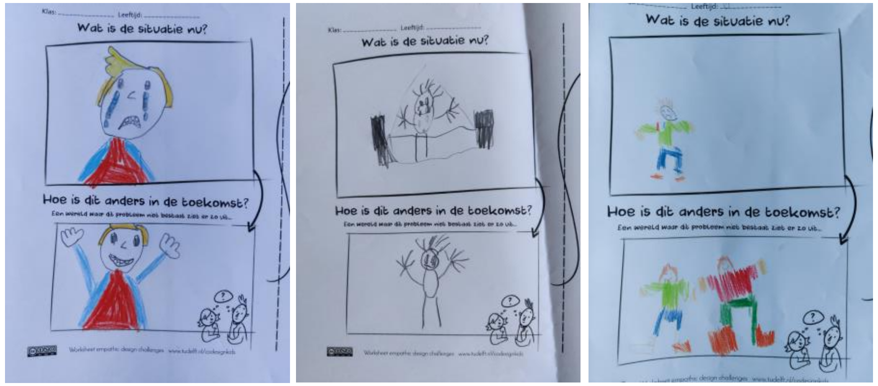
Session 5 | Emphatic design challenge



Session 5 | Emphatic design challenge



Session 5 | Emphatic design challenge



Appendix N

Class 3 Age 6-7 | Design session 5 | Idea brainstorm + dot voting technique

Session 5 | Idea brainstorm + dot voting technique

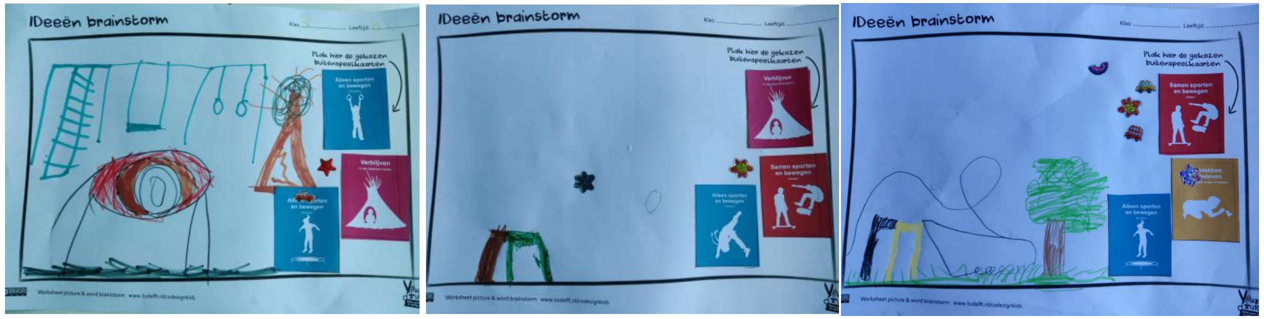
Appendix N

Class 3 Age 6-7 | Design session 5 | Idea brainstorm + dot voting technique

Session 5 | Idea brainstorm + dot voting technique

Class 3 Age 6-7 | Design session 5 | Idea brainstorm + dot voting technique

Session 5 | Idea brainstorm + dot voting technique

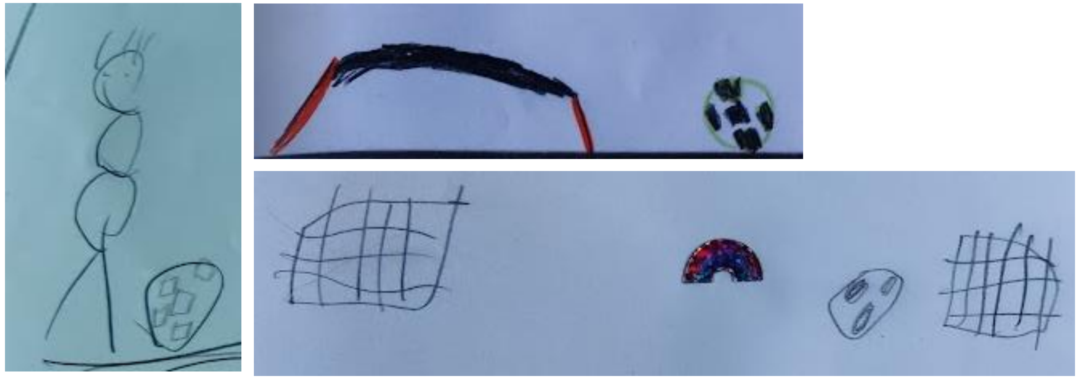


Class 3 Age 6-7 | Design session 5 | Idea brainstorm clusters

(Tree) house

Swinging and swaying

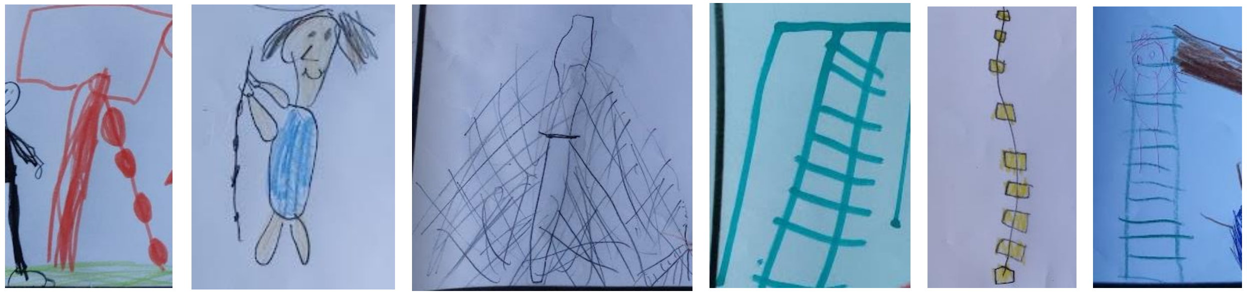
Soccer



Skating

BMX

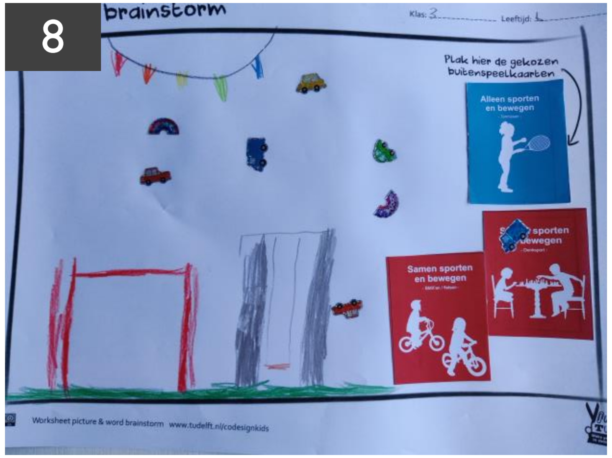
Climbing

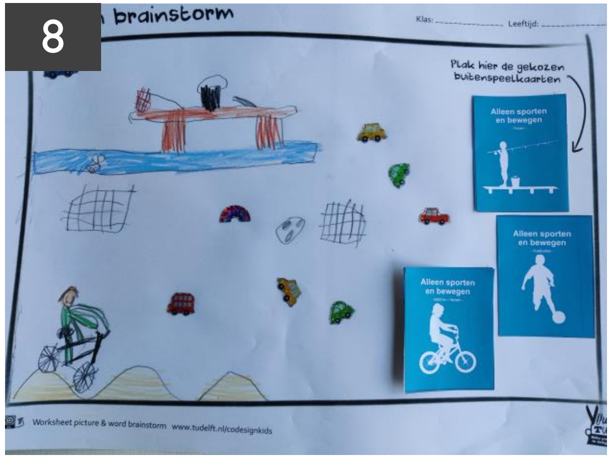


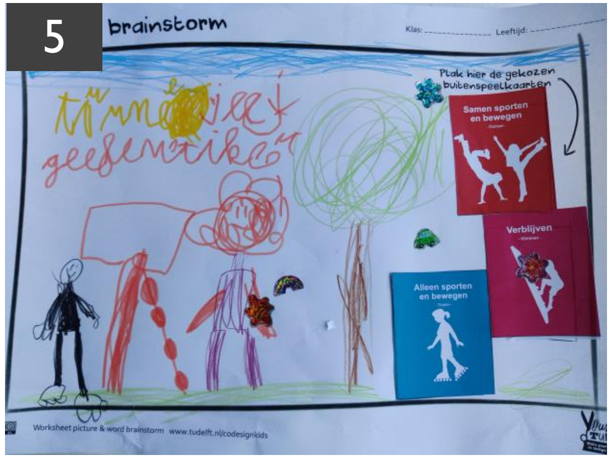
Trampoline

Class 3 Age 6-7 | Highest scores design session

Highest score (as rated by children)

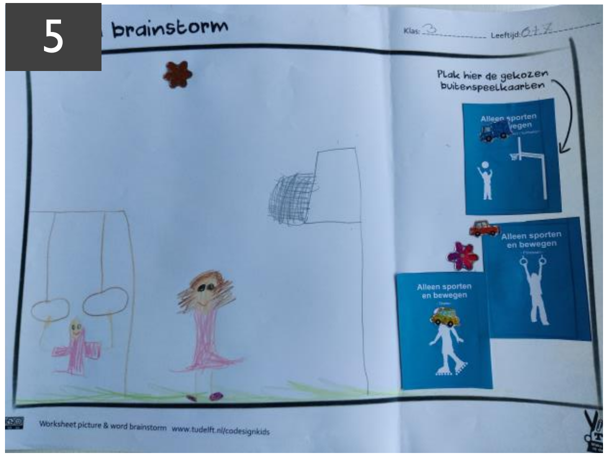


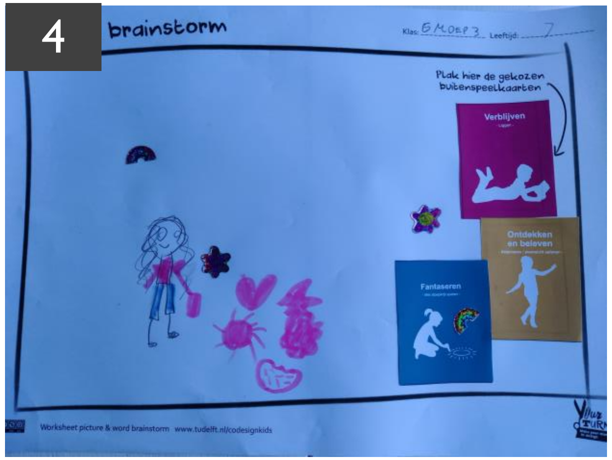


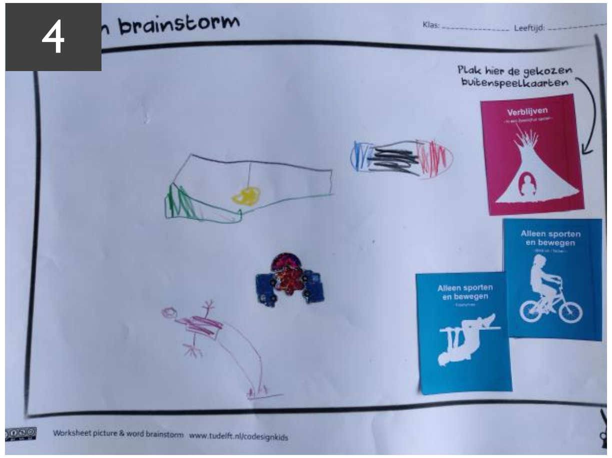


Class 3 age 6-7 | Highest scores design session

Highest score (as rated by children)



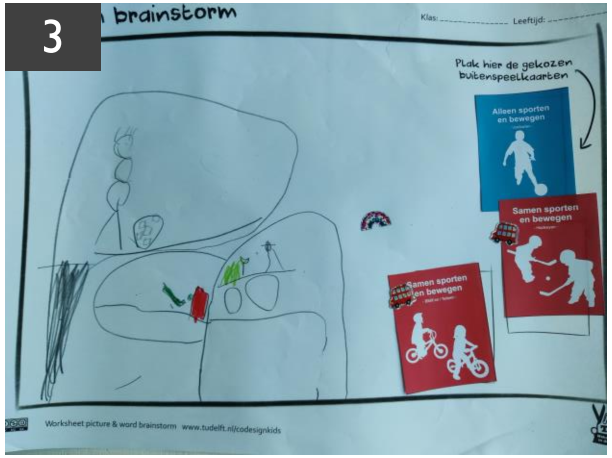


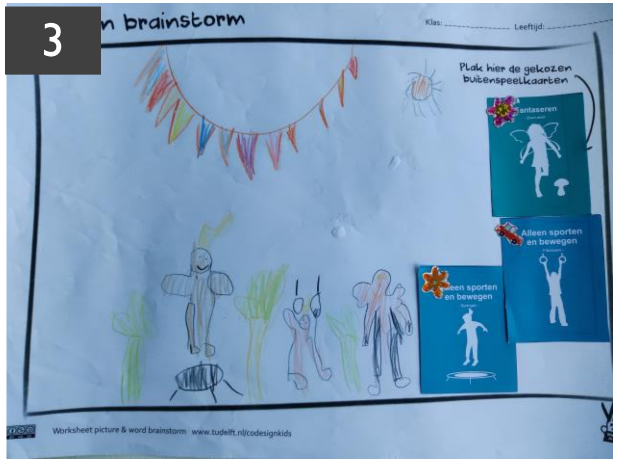


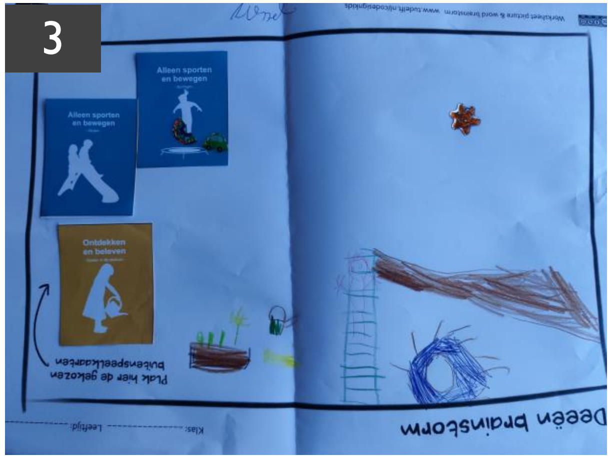
Appendix N

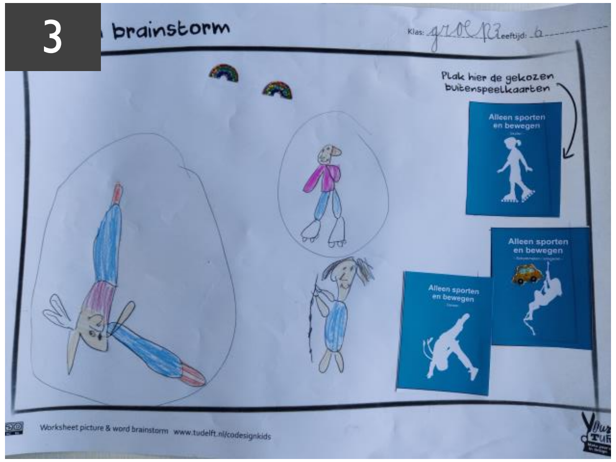
Class 3 Age 6-7 | Highest scores design session

Highest score (as rated by children)





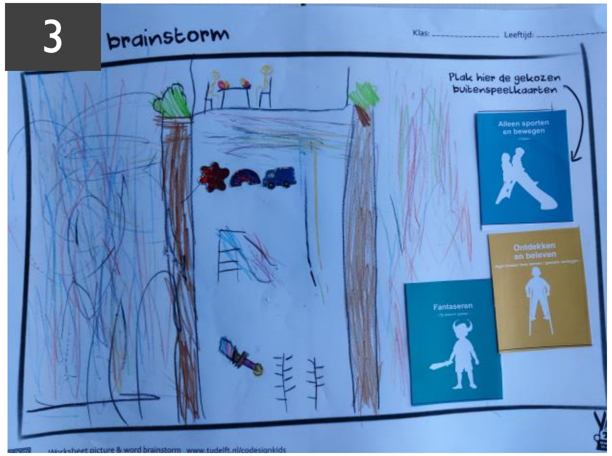


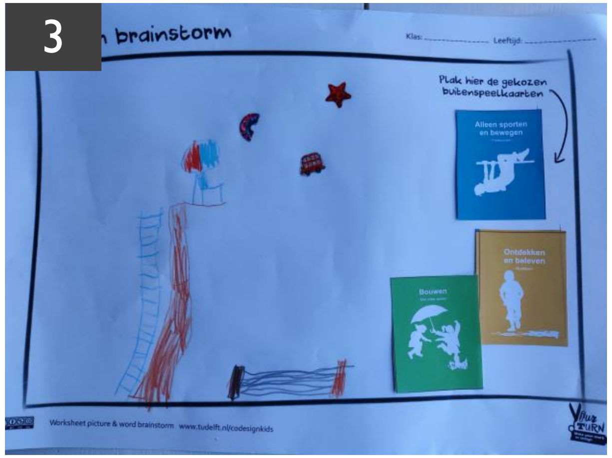


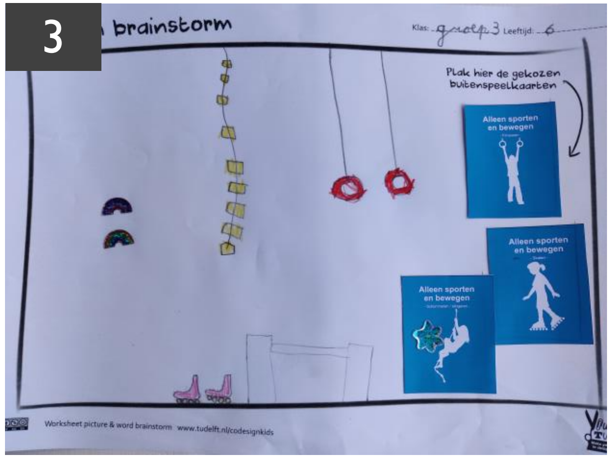
Appendix N

Class 3 age 6-7 | Highest scores design session

Highest score (as rated by children)





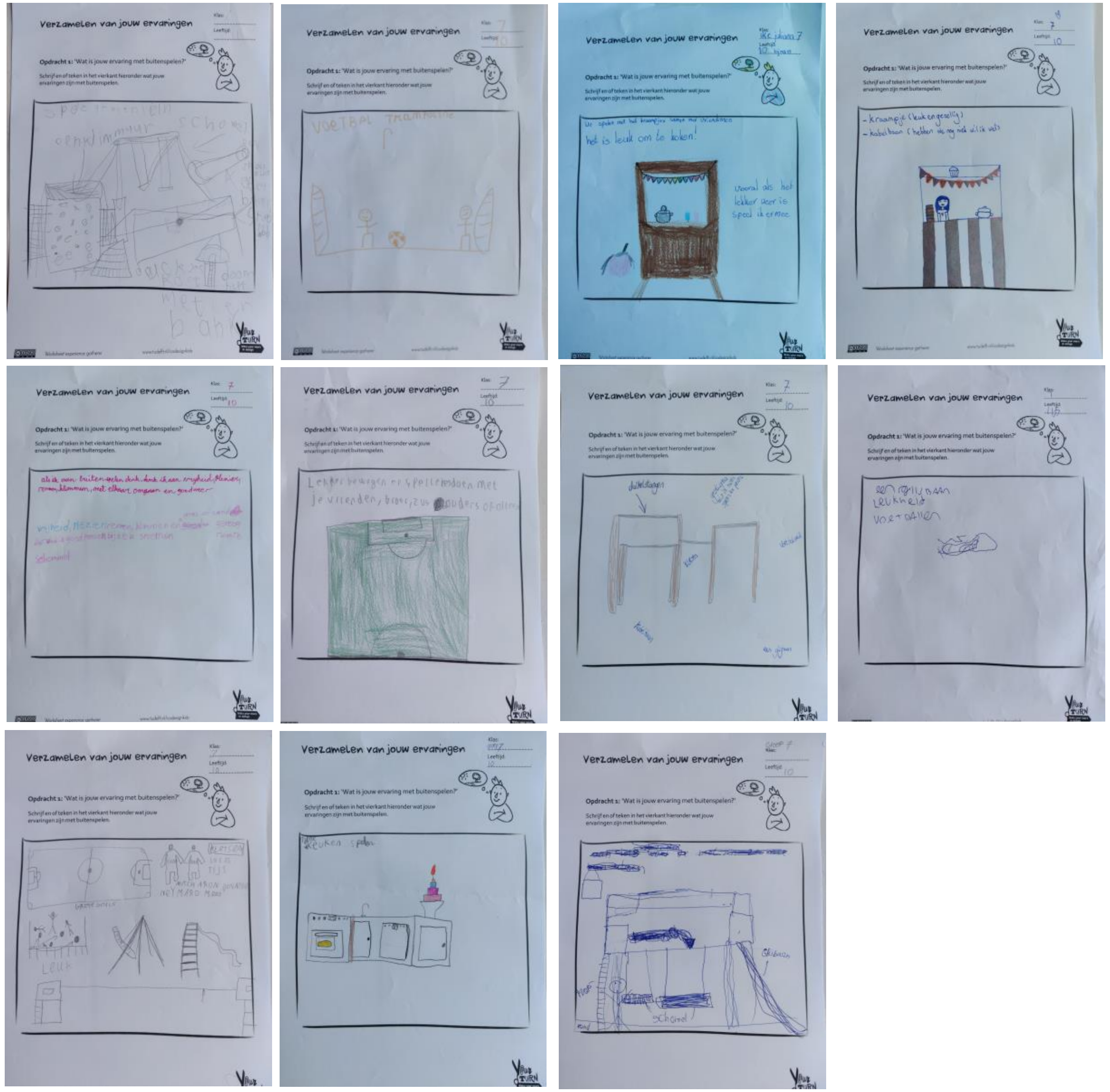


Class 7 Age 10-11 | Context mapping session 6 | Experience gatherer

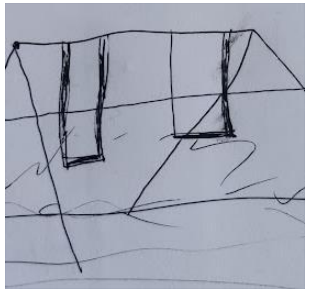
Session 6 | Experience gatherer

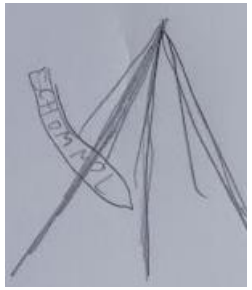
Class 7 Age 10-11 | Context mapping session 6 | Experience gatherer

Session 6 | Experience gatherer

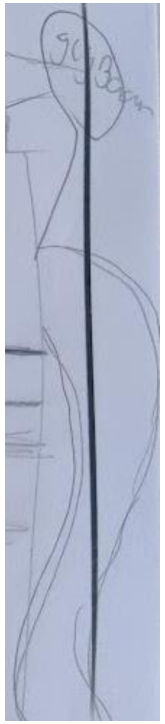
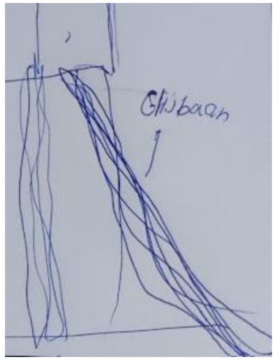


Swinging

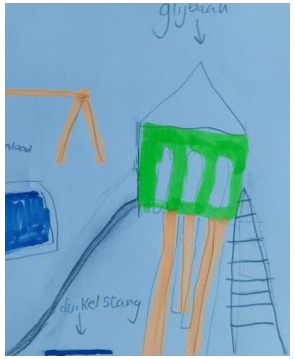


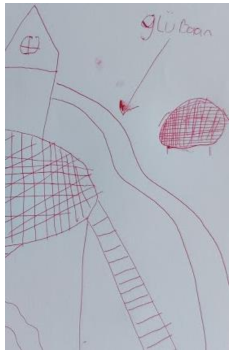




Sliding

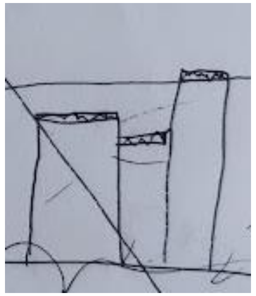
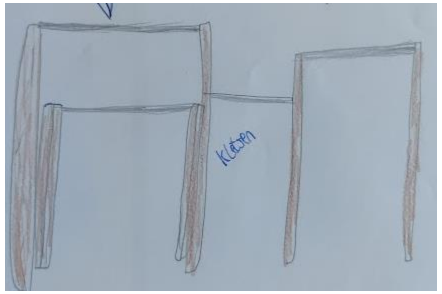



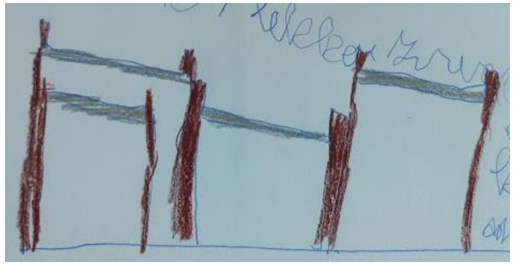


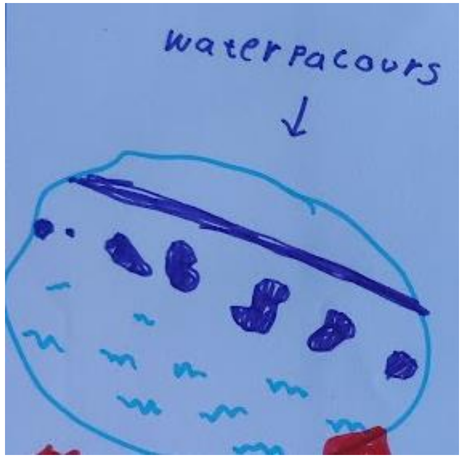


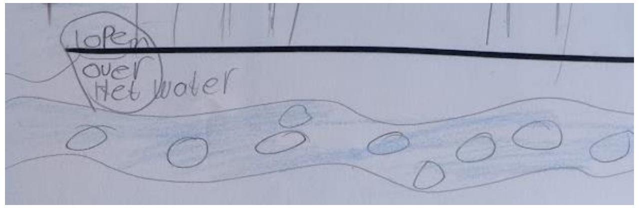

Tumble bars

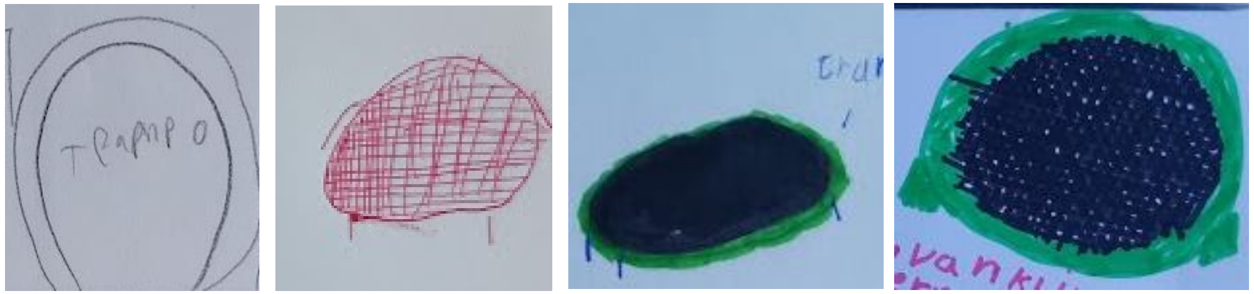




Water parkour

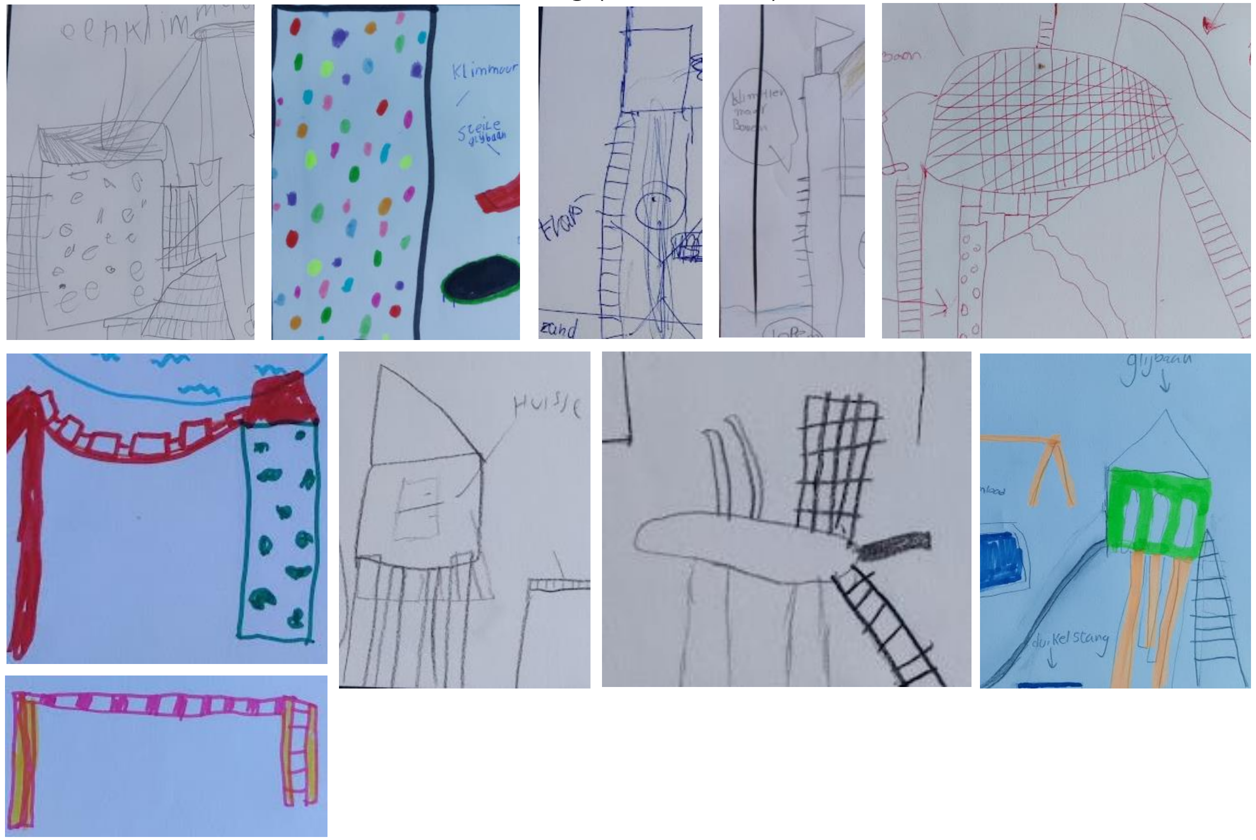




Trampoline



Climbing (to treehouse)

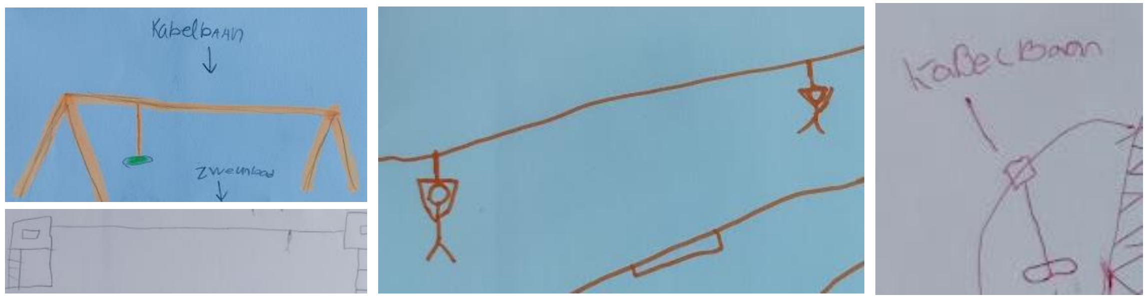


Appendix O

Class 7 Age 10-11 | Context mapping session 6 | Experience gatherer clusters

Playing soccer

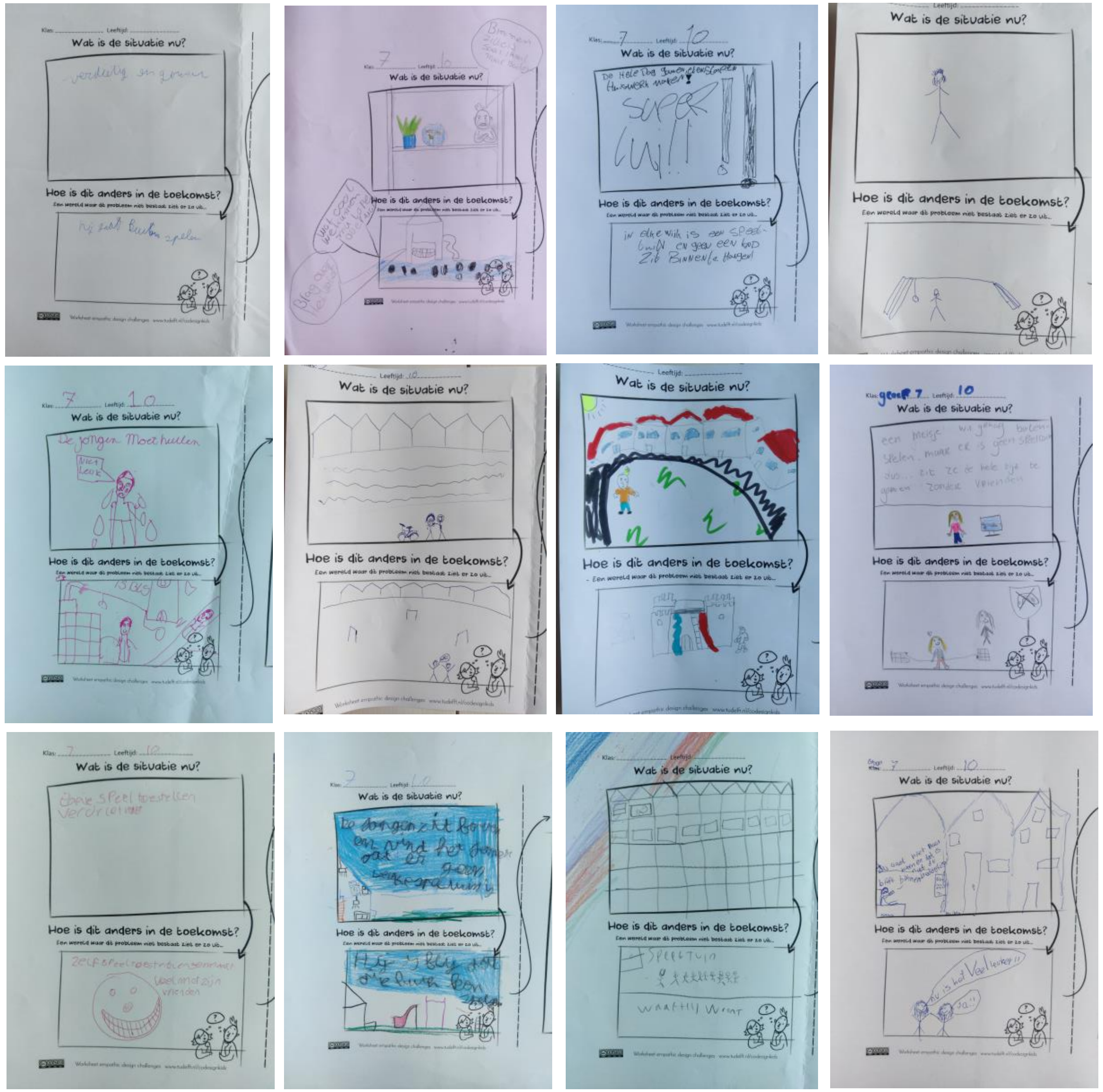
Cableway



Playing shop/ cooking (booth)

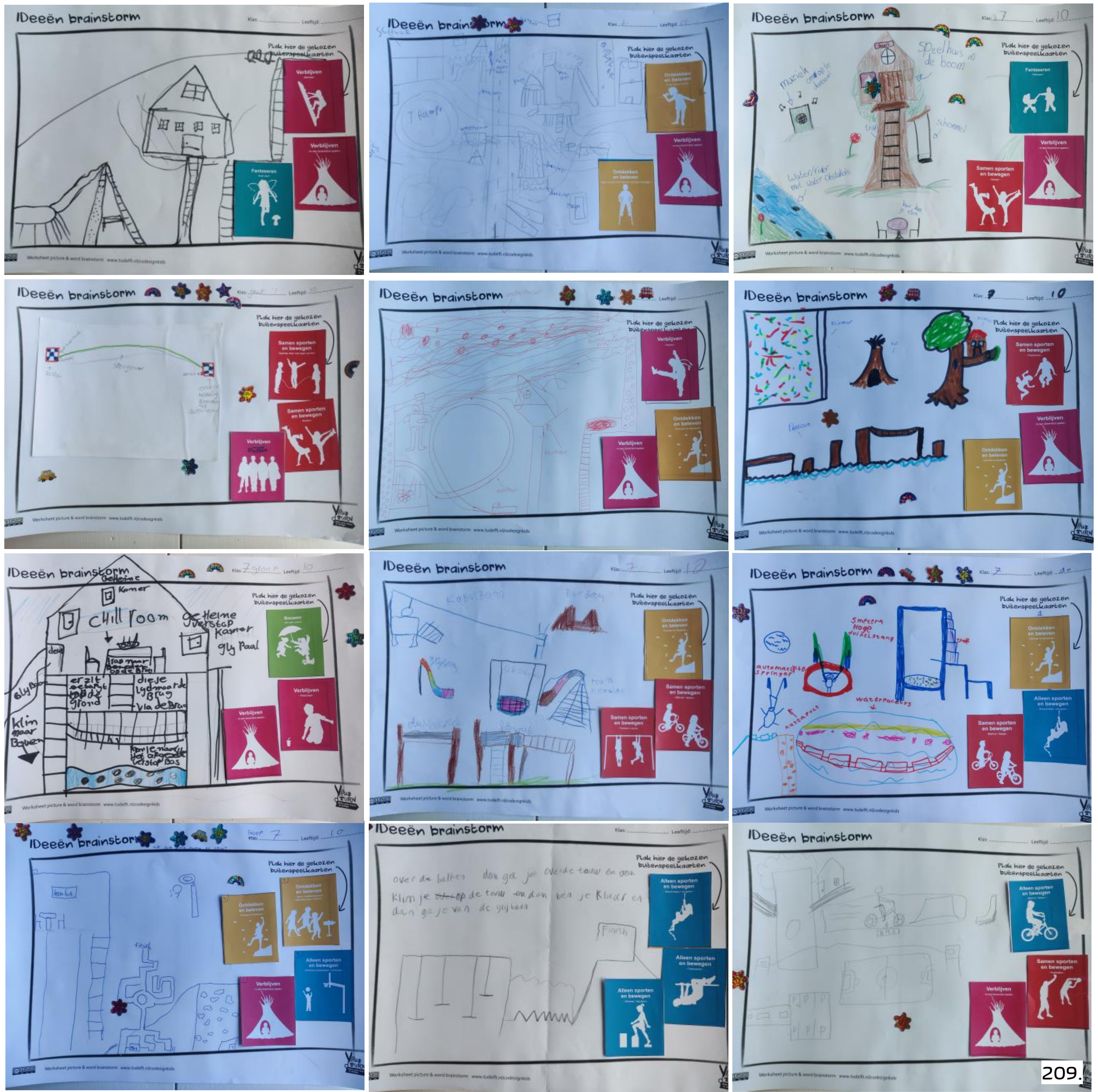
Session 6 | Emphatic design challenge

Session 6 | Emphatic design challenge



Class 7 Age 10-11 | Design session 6 | Idea brainstorm + dot voting technique

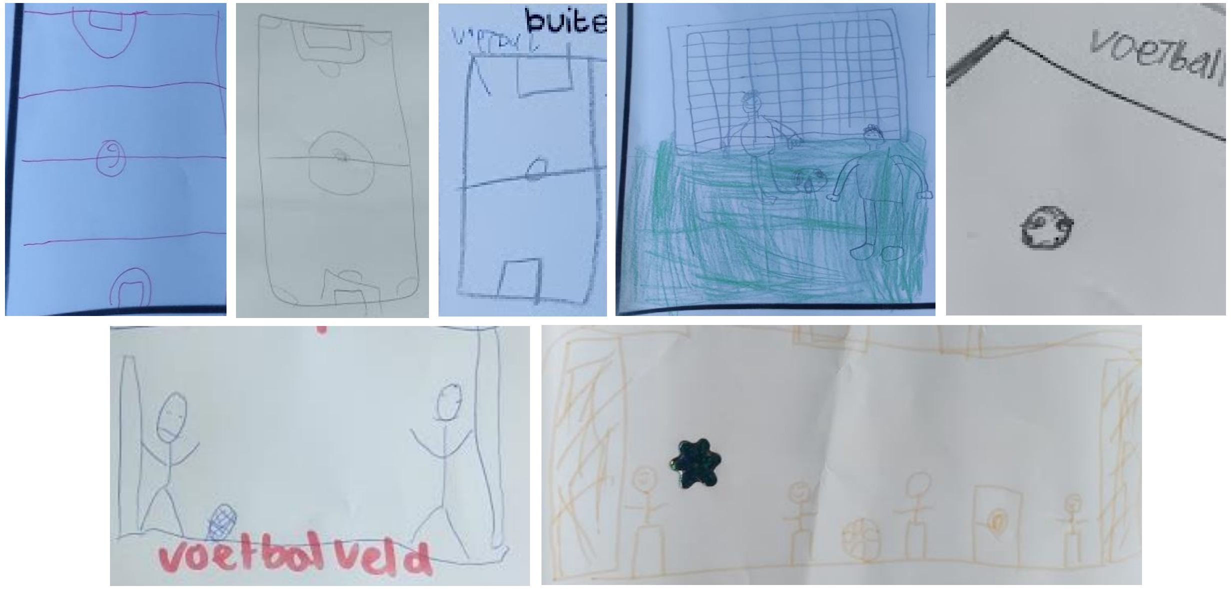
Session 6 | Idea brainstorm + dot voting technique



Class 7 Age 10-11 | Design session 6 | Idea brainstorm + dot voting technique

Session 6 | Idea brainstorm + dot voting technique

Soccer



Climbing

Treehouse

Class 7 Age 10-11 | Design session 6 | Idea brainstorm clusters

Sliding

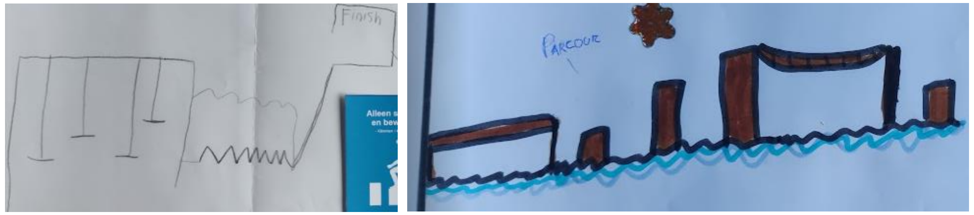
Swinging

BMX

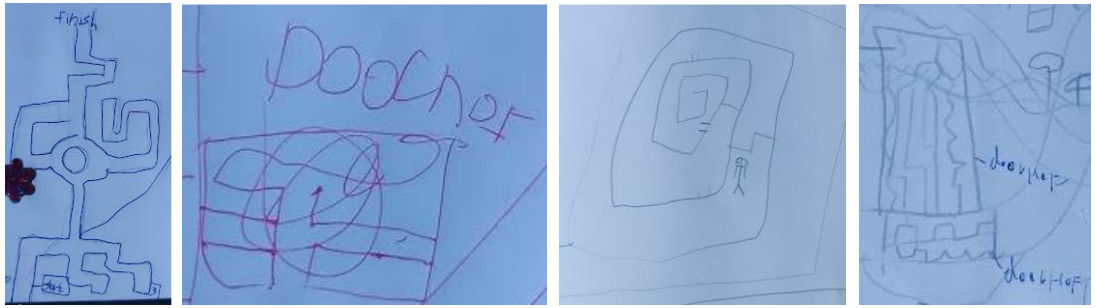
Class 7 Age 10-11 | Design session 6 | Idea brainstorm clusters

Play with water

Parkour

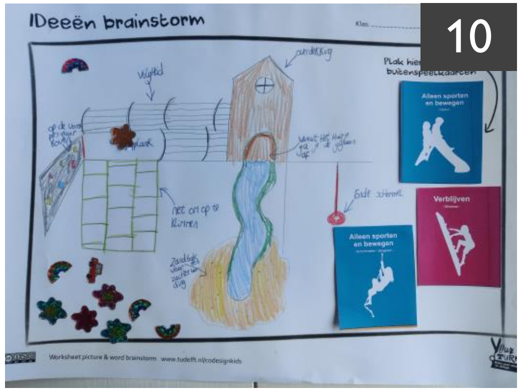


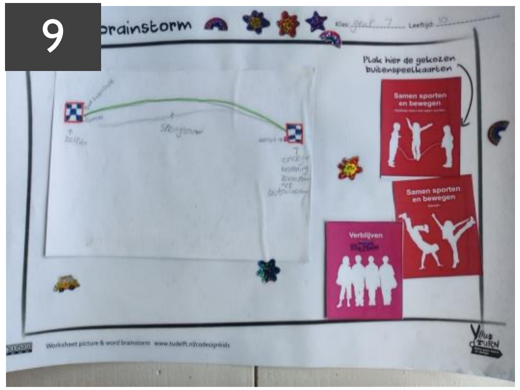
Maze

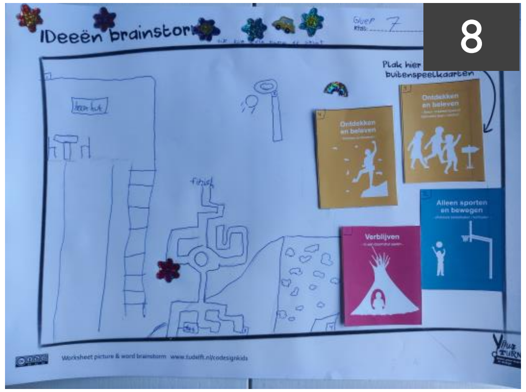


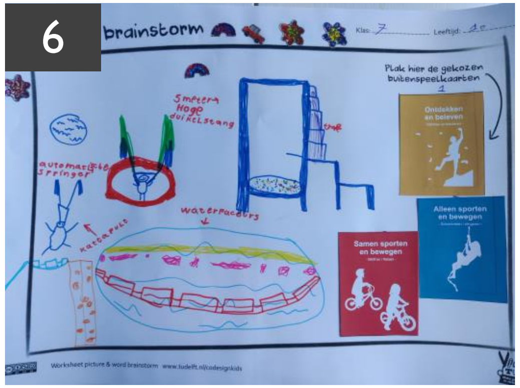
Class 7 Age 10-11 | Highest scores design session

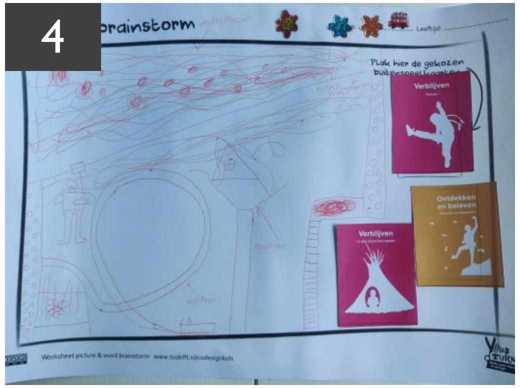
Highest score (as rated by children)





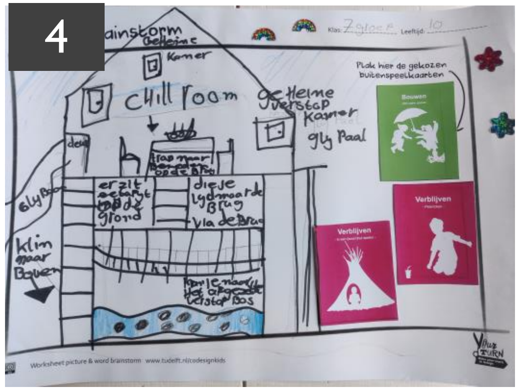


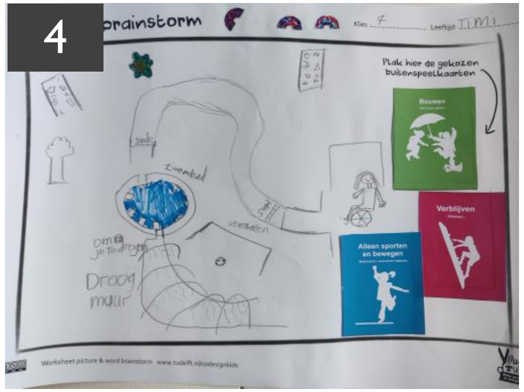


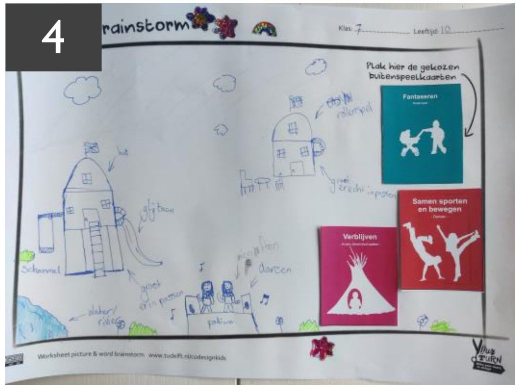


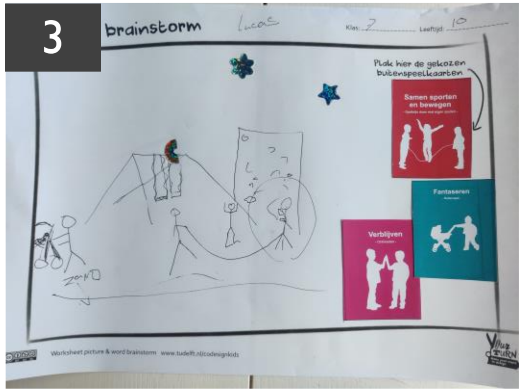
Class 7 age 10-11 | Highest scores design session

Highest score (as rated by children)









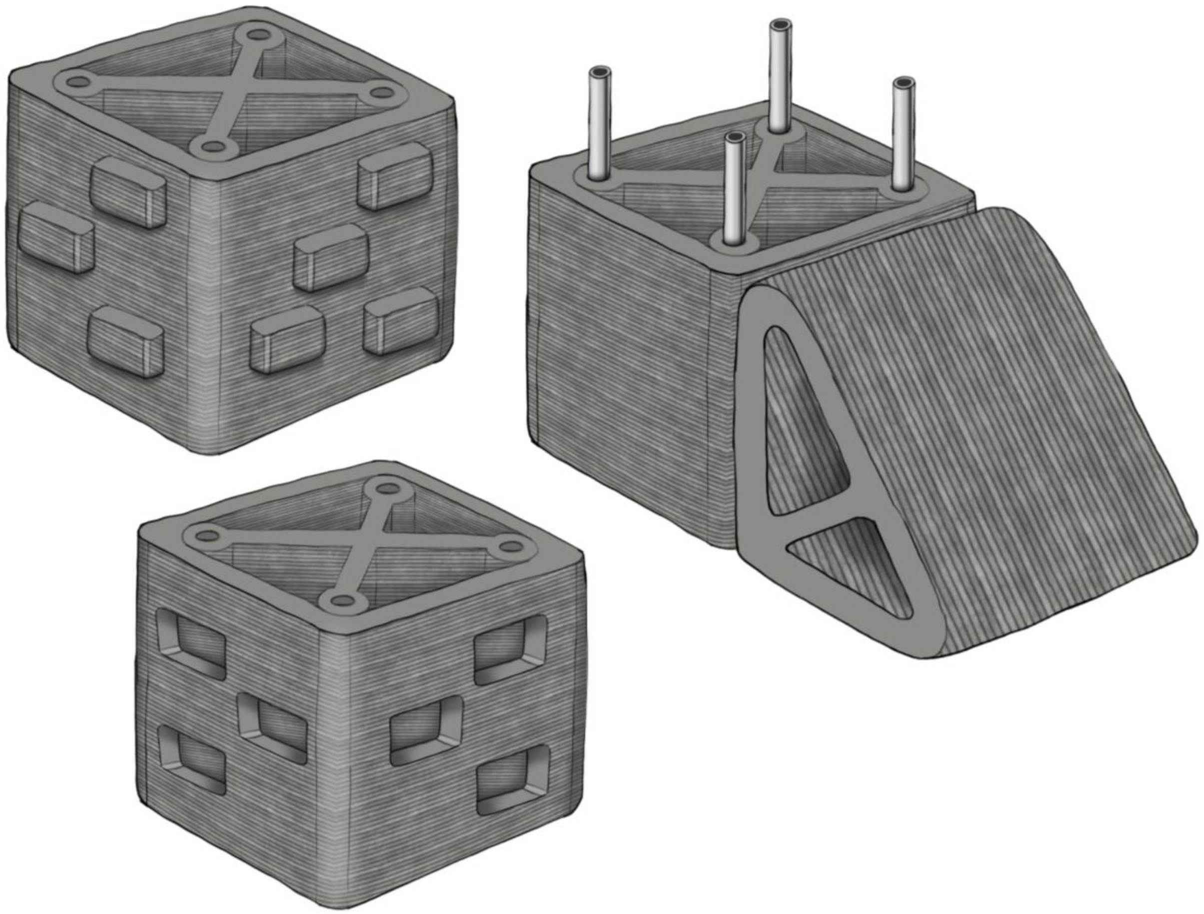
Appendix R

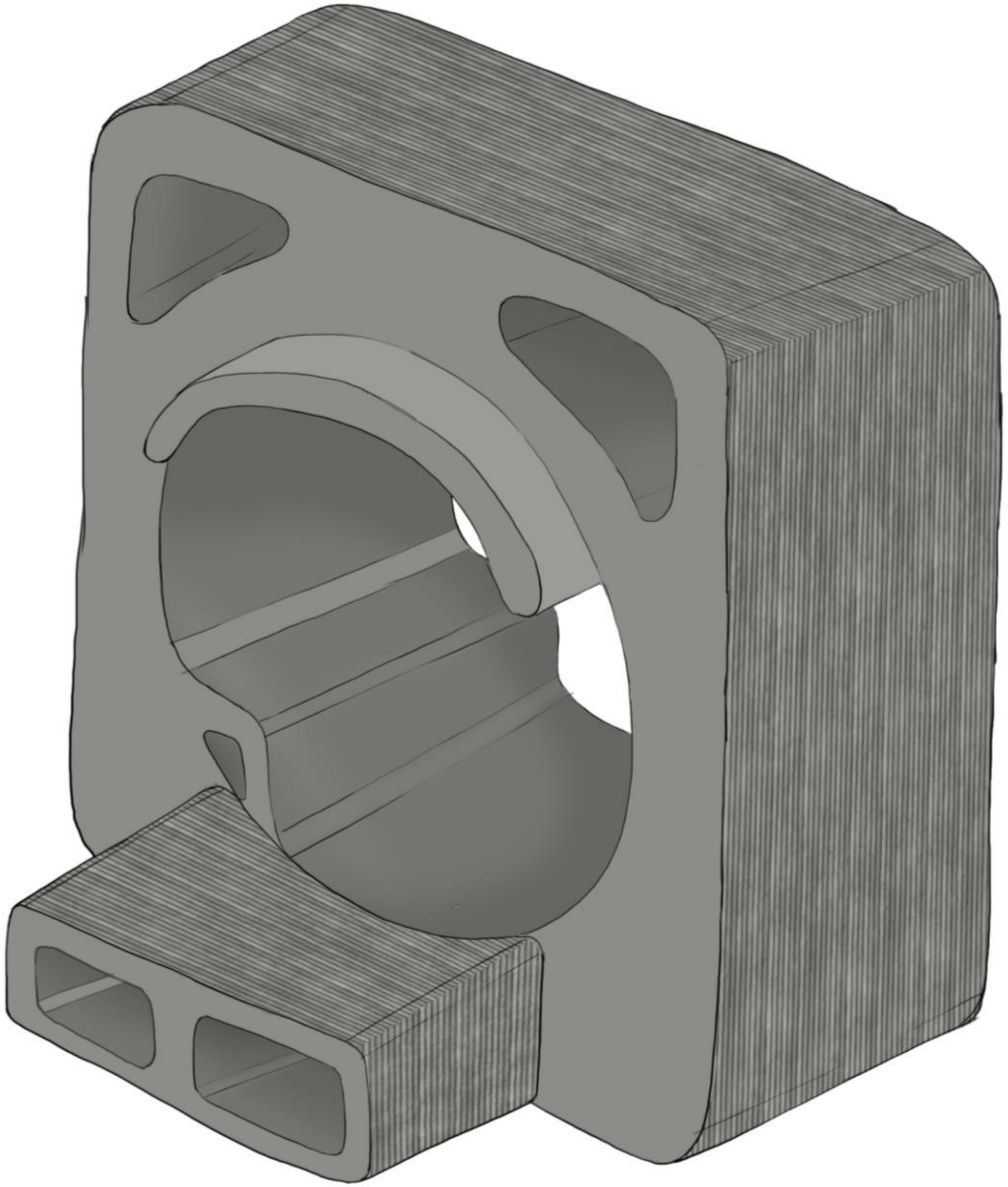
Inspiration board | 3D-printed structures

Appendix S

Design sketching of 3D-printed Geopolymer structures | Idea 1

The benefit of printing is that it is much easier to add openings for elements like steel poles. Furthermore, all these cubes are mostly hollow as it only needs material on the outside. Very large structures can also be created. For example, on the right you can see a big structure with a sitting area in the middle.



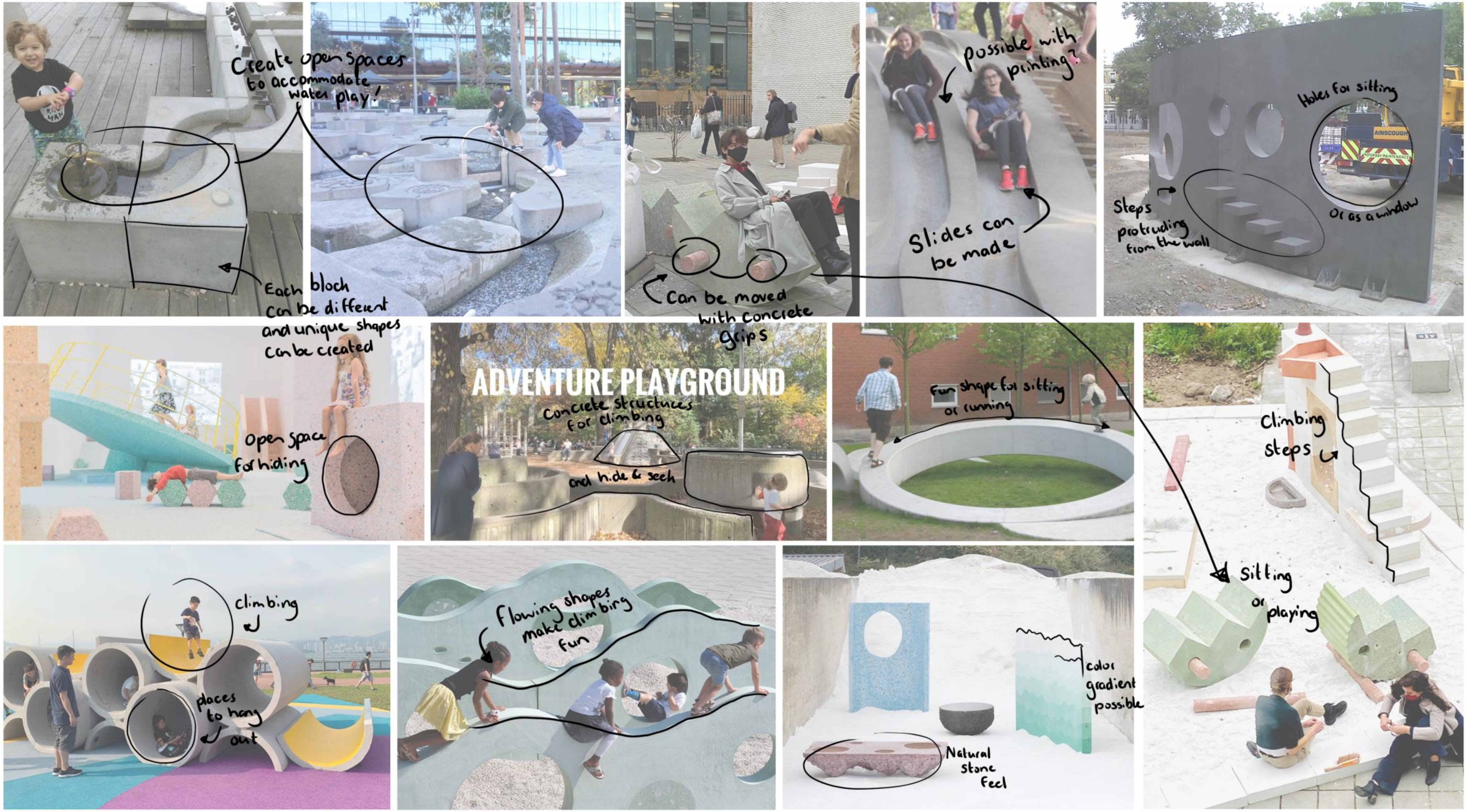


Appendix S

Design sketching of 3D-printed Geopolymer structures | Idea 2

Hexagon shaped play modules could be interesting as stacking them together creates an exciting structure. The modules can be hollow for children to hang-out in, and they can also be put on their side to be used as for example a planter. The bamboo poles can be integrated in a lot of different ways.

Inspiration board | PE concrete structures



Appendix T

Inspiration board | Playable non-PE concrete structures

Appendix U

Research on Geopolymer casting

Geopolymer, when in a paste form, can be poured into a mould. Once the Geopolymer hardens the resulting product can be taken out of the mould. There is no difference in using Geopolymer or traditional concrete in these moulds. The only difference is the type of mould-release agent [182]. Therefore, no new type of moulds need to be created for Geopolymer products. Furthermore, these moulds, when made from steel, can be used many times (a thousand times if they are properly maintained. The main cause of a defected mould is wear) [182].

Mould types
Each mould is custom produced to be able to make the Geopolymer shape that is needed. Different types of moulds exist, which can vary in size, releasing mechanism and complexity.

Mould to create tubular elements
The mould as can be seen in Figure 98 (left) is made by constructing a steel 'box', in which the soft Geopolymer can be poured. This results in the product as can be seen in Figure 98 (right). It is taken out of the mould by moving the two steel walls and lifted from the shaft in the middle.

Mould to create complex shapes
The mould as can be seen in Figure 99 (left) is made by milling the shape of the product out of a block of steel. This mould can be filled with the soft material and when this hardens it results in the product as can be seen in Figure 99 (right). It is taken out by tilting the mould. With this technique rounded and intricate shapes can be produced.

Mould to create structures with a sham edge
The mould as can be seen in Figure 100 has two rotating side walls which are needed to remove the Geopolymer product as the underside has an outwards edge. This results in the product as can be seen in Figure 100.

Mould to create flat structures
The mould as can be seen in Figure 101 (left) has a rotating 'door', needed to remove the intricate shape of the resulting product (Figure 101 (right)). These products are removed by using suction cups.

Blockmoulds
Blockmoulds are a very interesting mould as it consists of several components which can be interchanged to create different products (Figure 102 (left)). This way, only additional side or middle walls are needed instead of creating a whole new mould for each individual product. These moulds are filled from the top with soft Geopolymer and after this has hardened the walls are removed, and the resulting product (Figure 102 (right)) can be lifted out.

Figure 98: Mould to create tubular elements (left) and final product (right) [352]

Appendix U

Research on Geopolymer casting

Figure 99: Mould to create complex shapes (left) and final product (right) [353]

Figure 100: Mould to create structures with a sham edge [354]

Figure 101: Mould to create flat structures (left) and final product (right) [355]

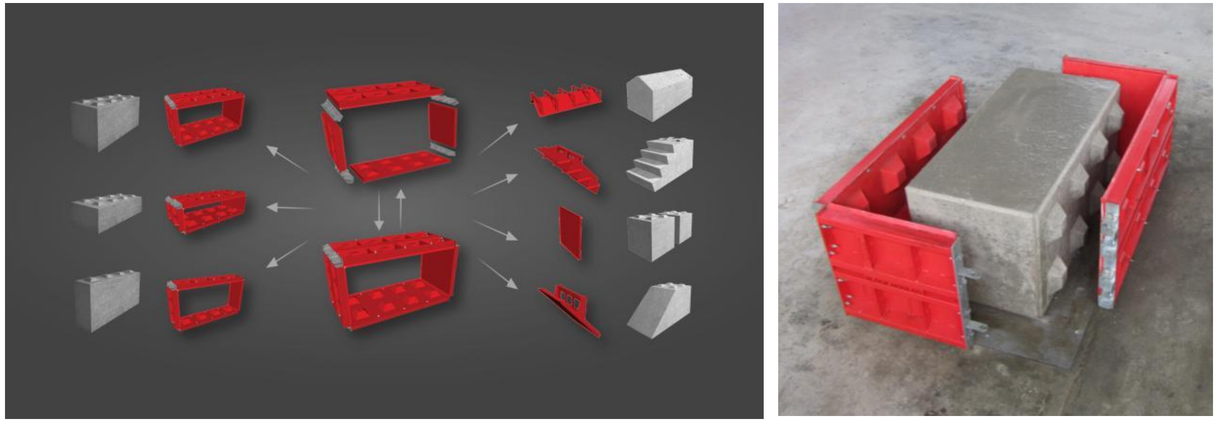


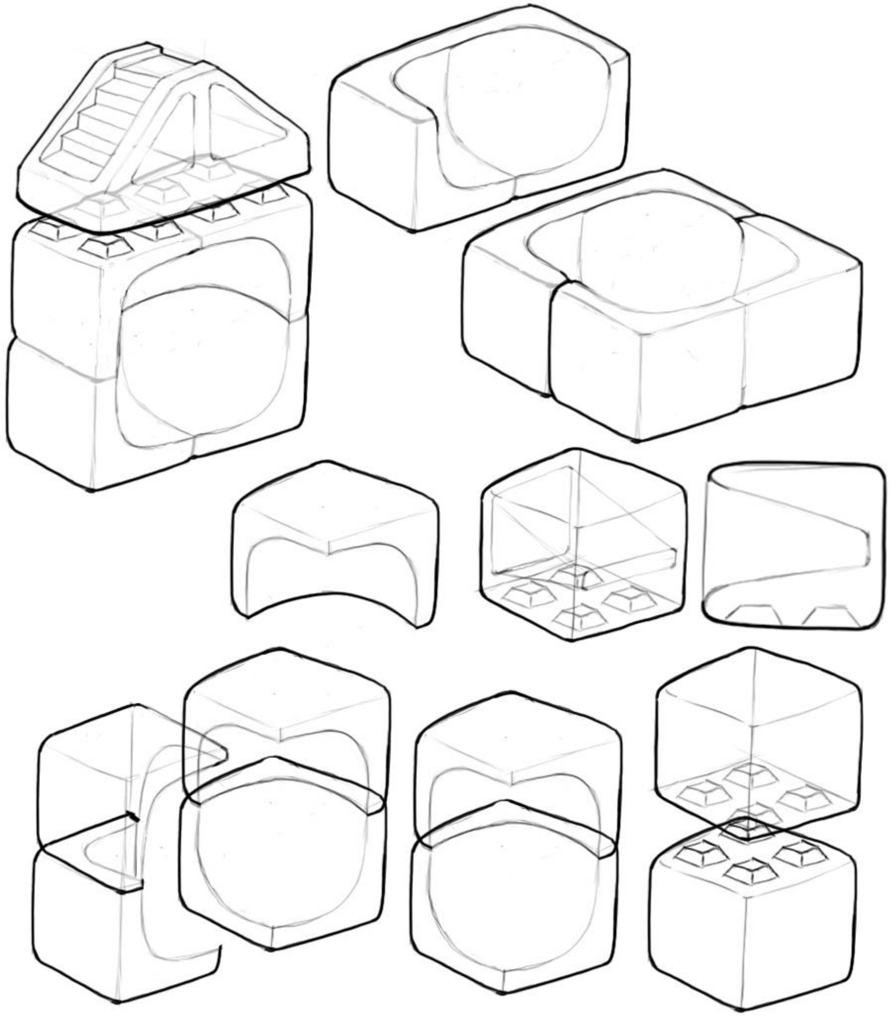
Figure 102: Multipurpose mould to create different shaped blocks (left) and final product (right) [356]

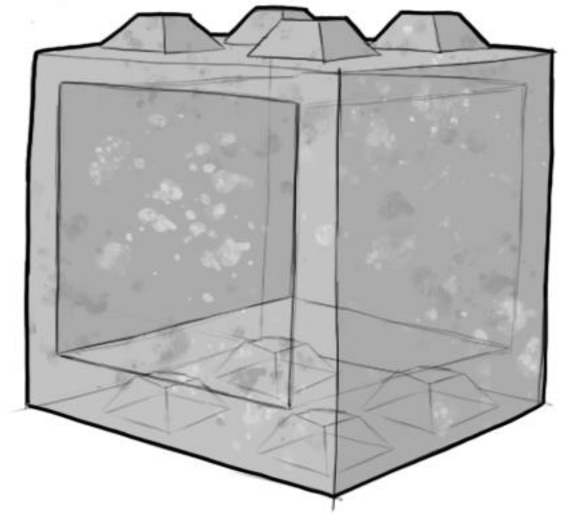
Appendix V

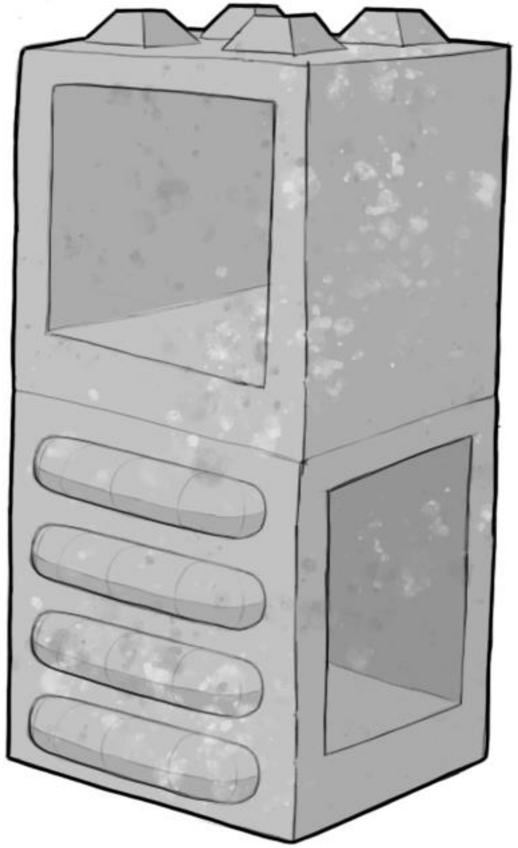
Design sketching of casted Geopolymer structures | Idea 1

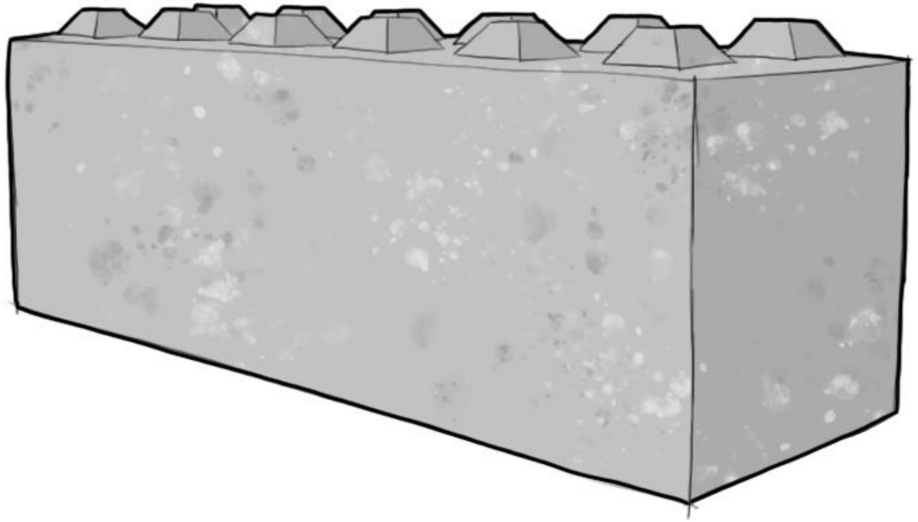
The first idea is based on the existing concrete blocks, which can be created with the blockmoulds as described in Appendix U. By making the Geopolymer modules compatible with existing concrete blocks they can be stacked on top of each. This decreases the need to produce some new blocks, as the concrete blocks can serve as the first layer of the playground structure. You might even be able to make changes to the existing blockmoulds, by producing new custom pieces which can be inserted in the blockmould frames.

However, after having several conversations with producers of these concrete blocks, it was concluded that every manufacturer produces their own blocks with a different size and stud placement. Therefore, this is not an efficient design.





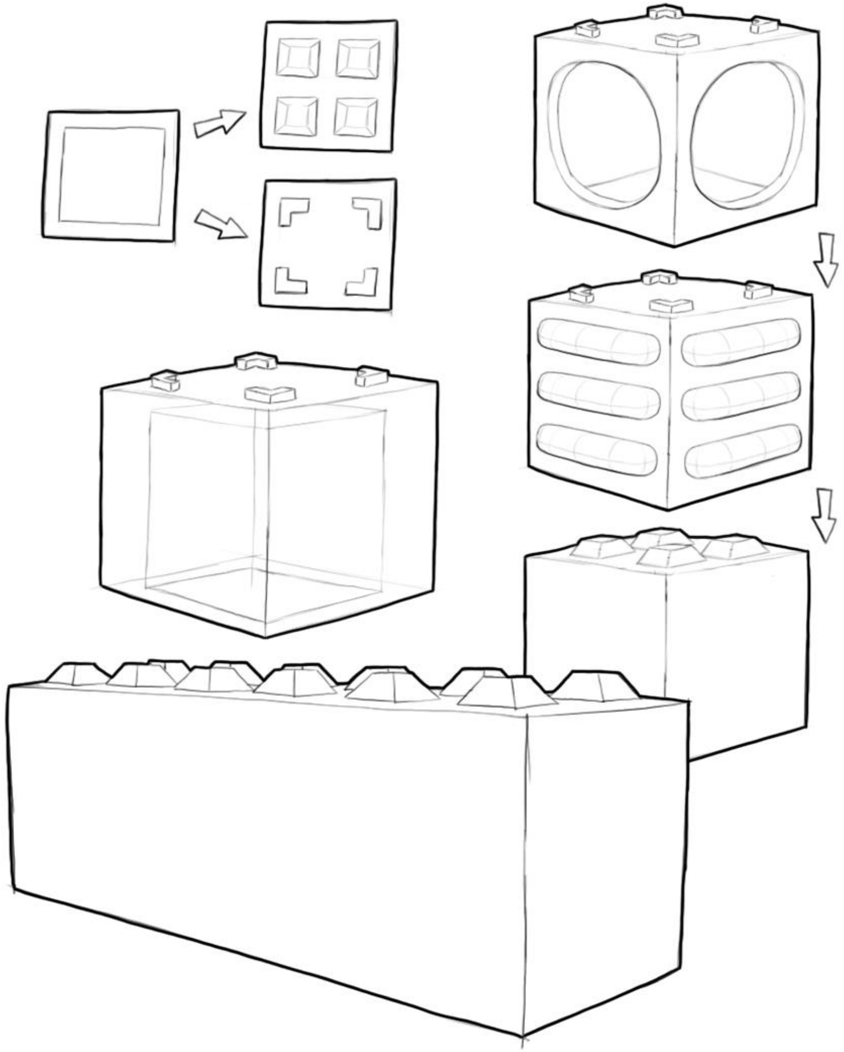


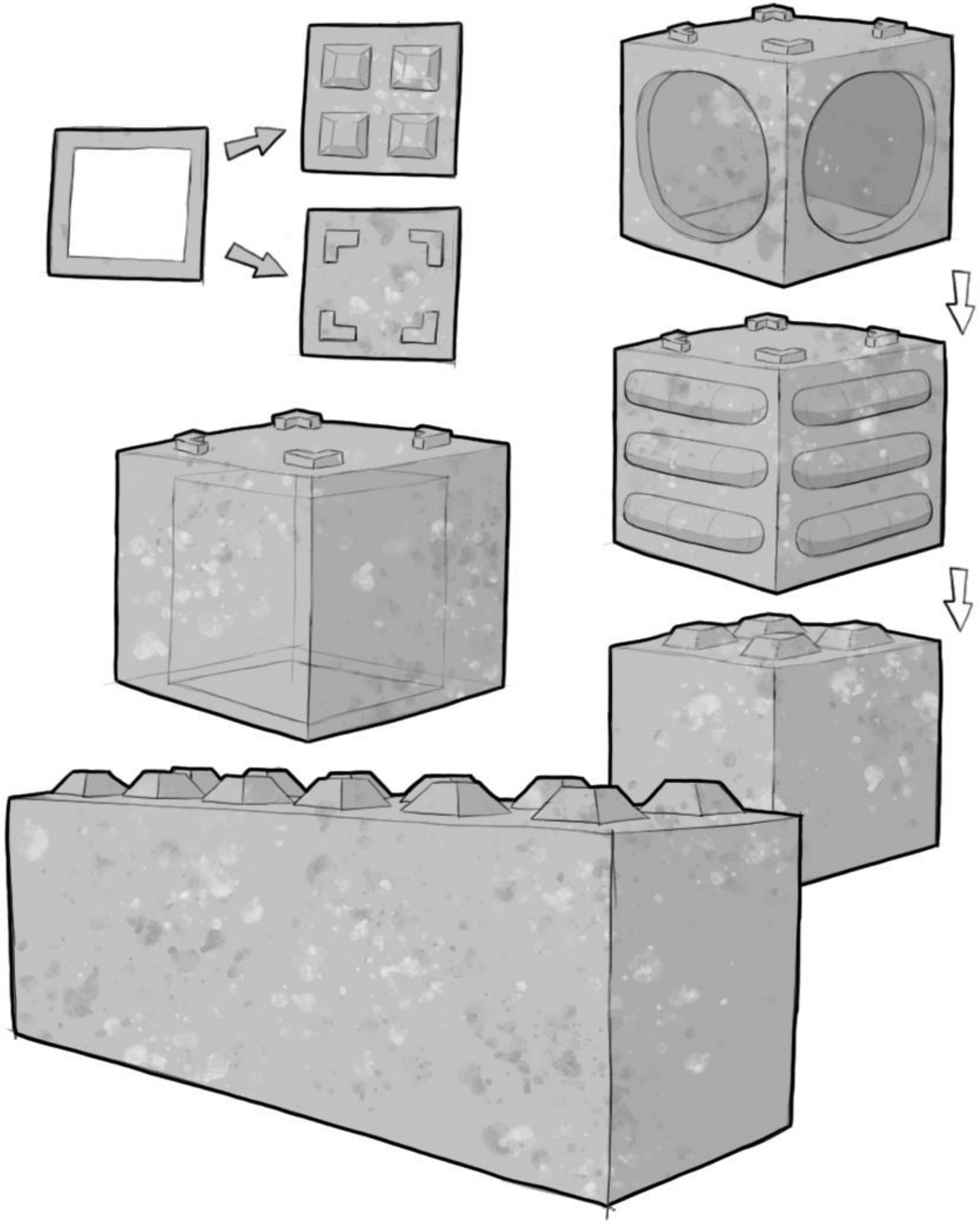


Appendix V

Design sketching of casted Geopolymer structures | Idea 2

The second idea is also based on the existing concrete blocks. However, instead of creating playground blocks which have this specific stud pattern on the top and bottom, which does not fit on every concrete block, the block is open at the bottom. This allows the blocks to be placed on different concrete blocks, making it more versatile. Studs on the top of the PE blocks allow the individual blocks to be stacked on top of each other. Climbing elements can be added to the blocks within the mould. Holes or openings have to be made during post-processing.



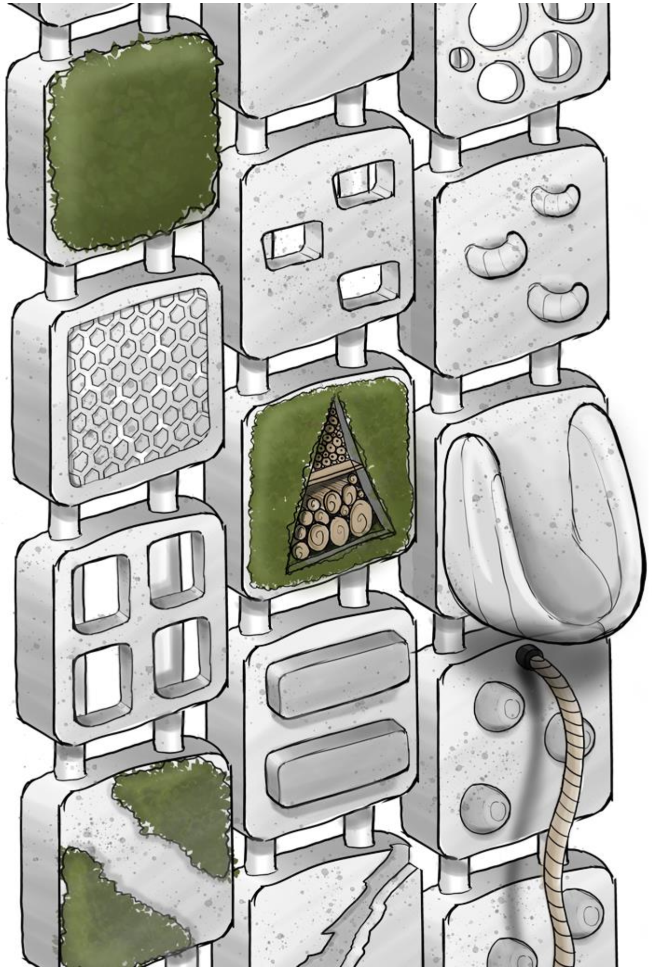


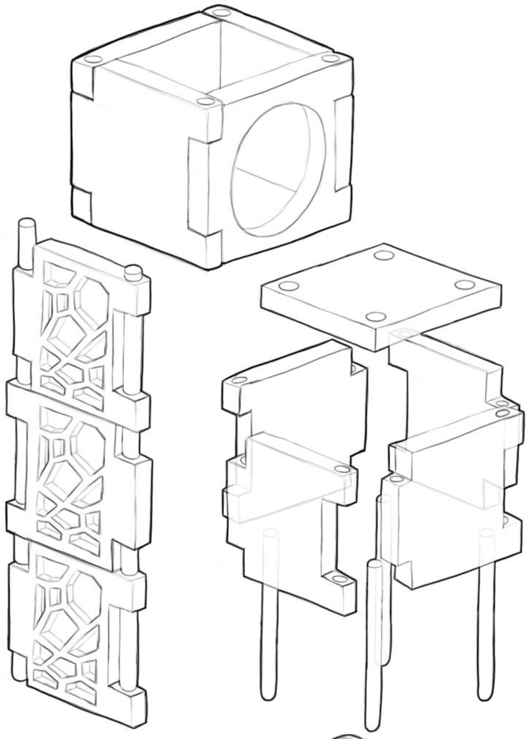
Appendix V

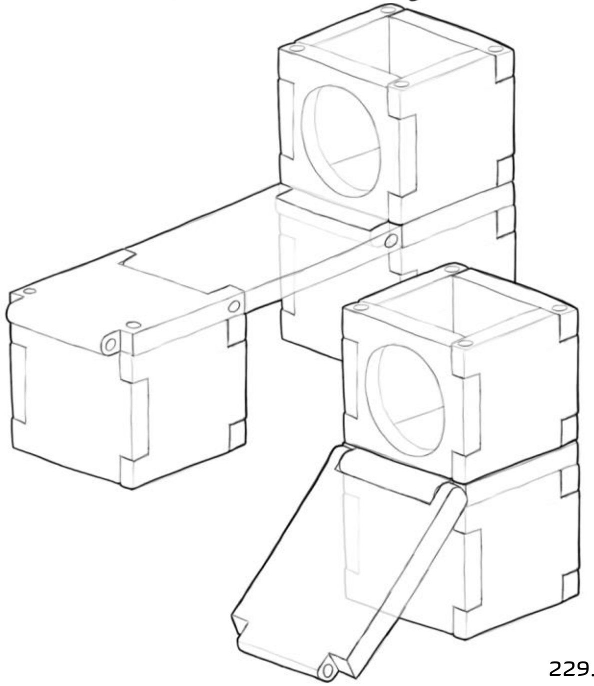
Design sketching of casted Geopolymer structures | Idea 3

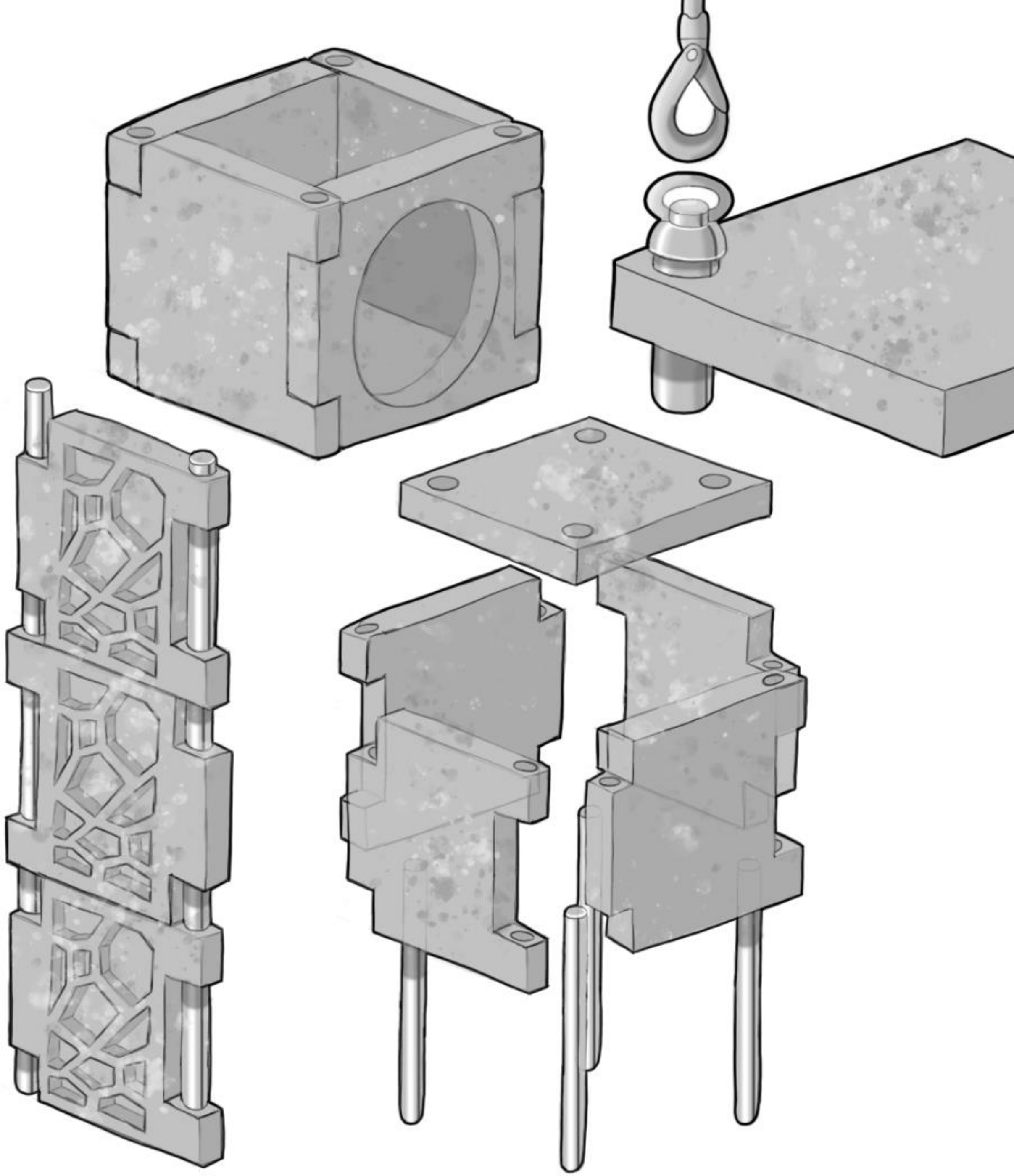
The third idea consists of slabs rather than blocks. These slabs can be connected by means of sliding them over steel tubes. This allows for creating walls (with a thickness of one slab), cubes and ramps. As a cube consists of several slabs, each cube can be uniquely designed to accommodate for the needed play functions. Furthermore, all slabs have the same size and basic shape. Therefore, altercations, such as openings and climbing elements, could be made by adding a piece to the existing mould instead of having to produce several moulds.

Placing the slabs around steel poles keeps them in place, which disables them to collapse or be stolen. Special hooked caps on the ends of these poles allow for easy lifting of the modules.





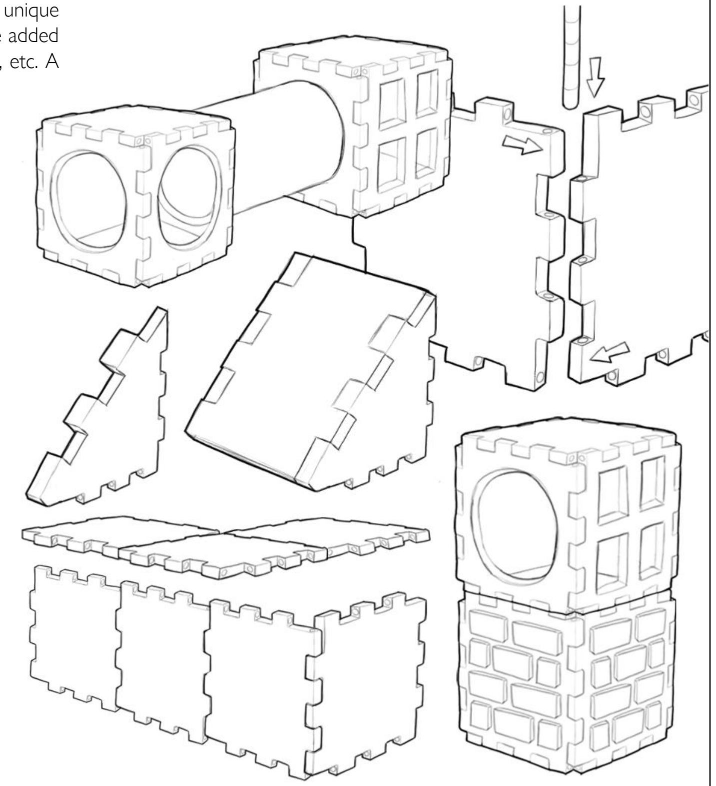


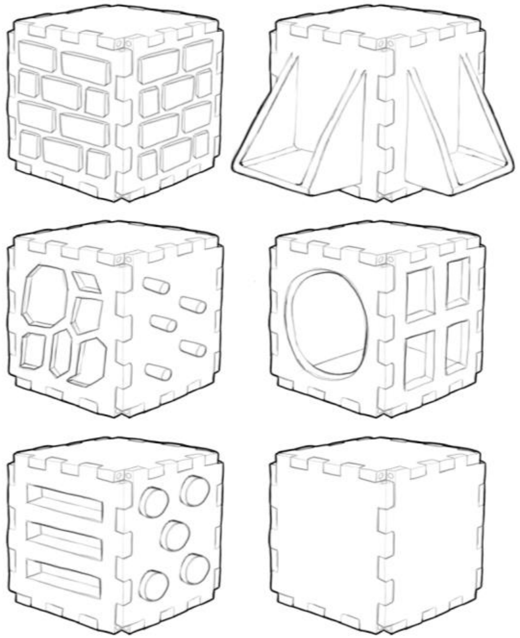


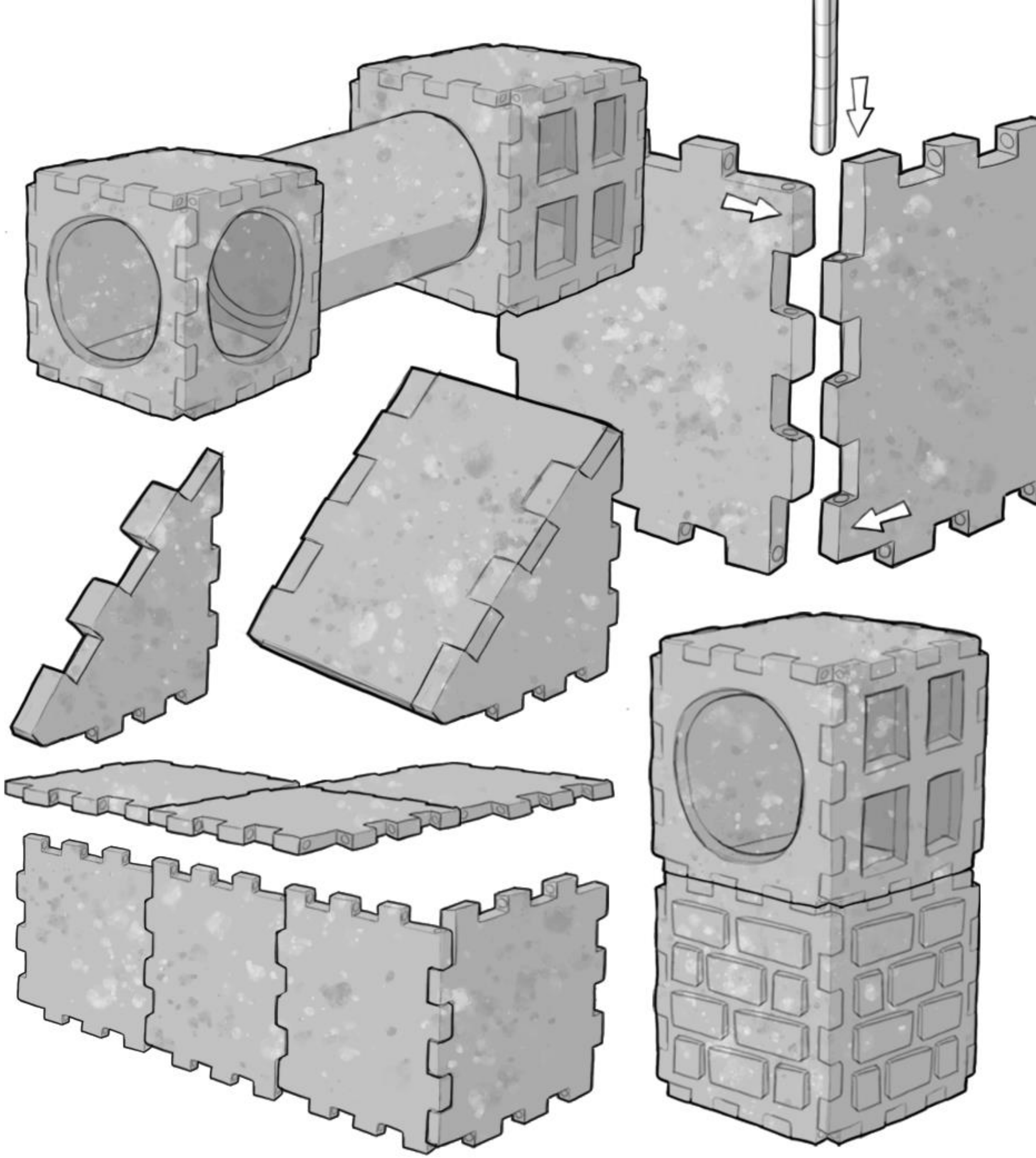
Appendix V

Design sketching of casted Geopolymer structures | Idea 4

The fourth idea is based on plastic children's toys which can click into each other which enables children to build houses and other structures. This concept is similar to concept 3 as it consists of a plethora of different Geopolymer slabs which can be connected to each other to create unique structures. Each slab can have a unique design, providing a specific play function. Textures could also be added to these slabs, such as a brick pattern, to create houses, castles, etc. A triangle shaped slab can be used to create slopes or roofs.



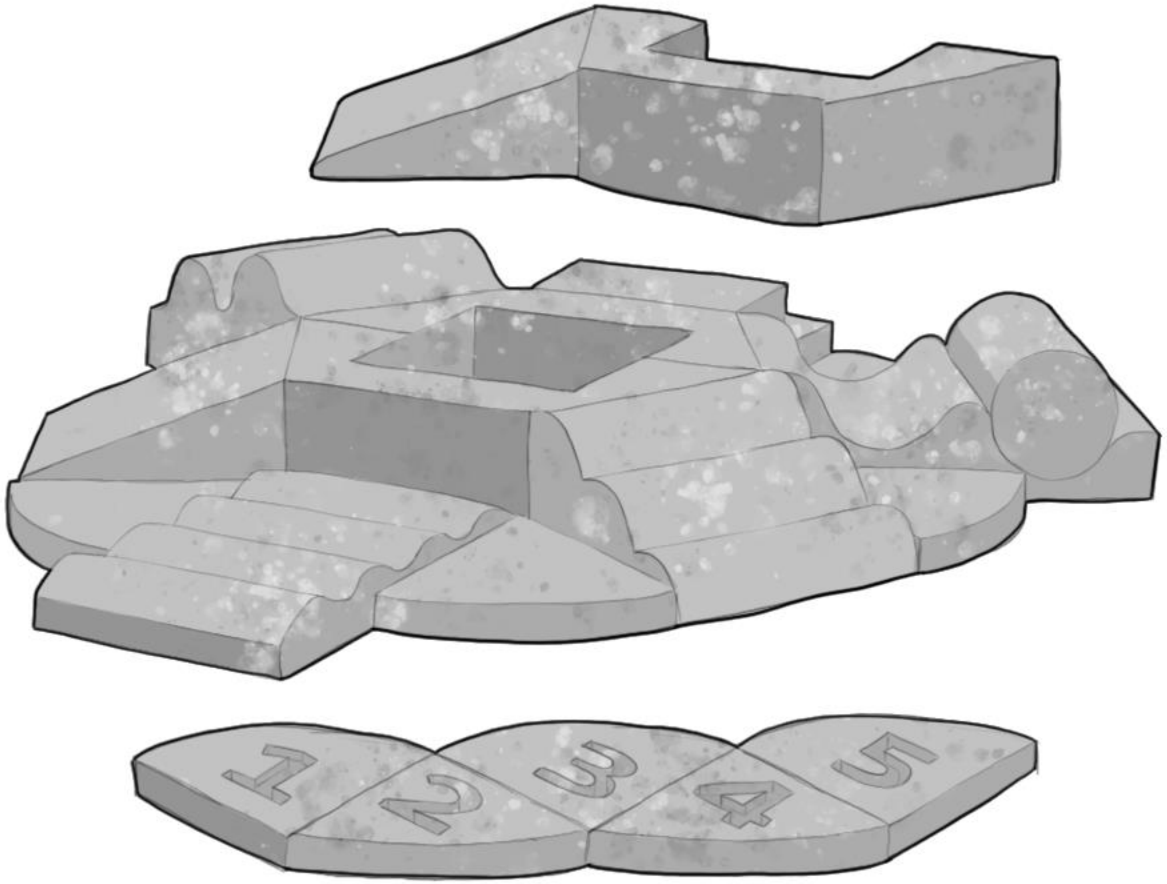




Appendix V

Design sketching of casted Geopolymer structures | idea 5

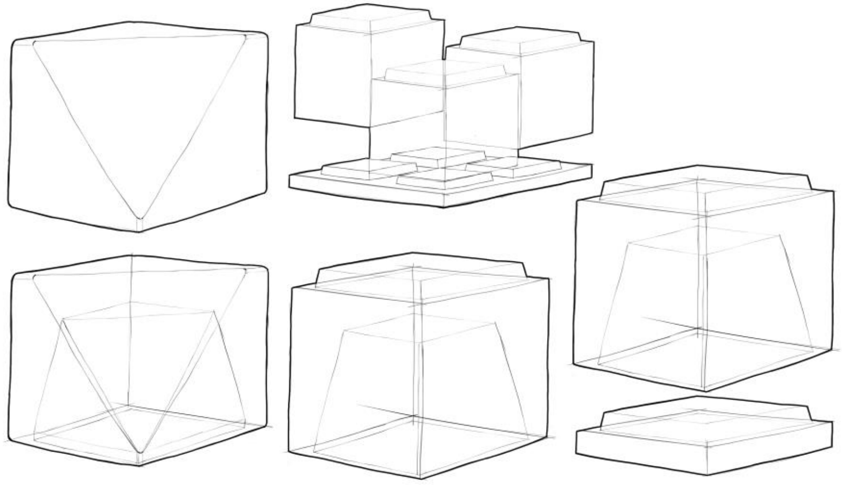
The fifth idea allows for a lot of freedom, as random Geopolymer shapes can be configurated in any way possible. The modules can be square, round, sloped and also have embossing which could be used to add a gaming element to the playground. For example, adding numbers can encourage children to play hopscotch. A downside of this concept is that it would take a lot of different moulds to create these shapes. Furthermore, if these shapes are not hollow (which is sometimes difficult to do in Geopolymer moulds) they will become very heavy.

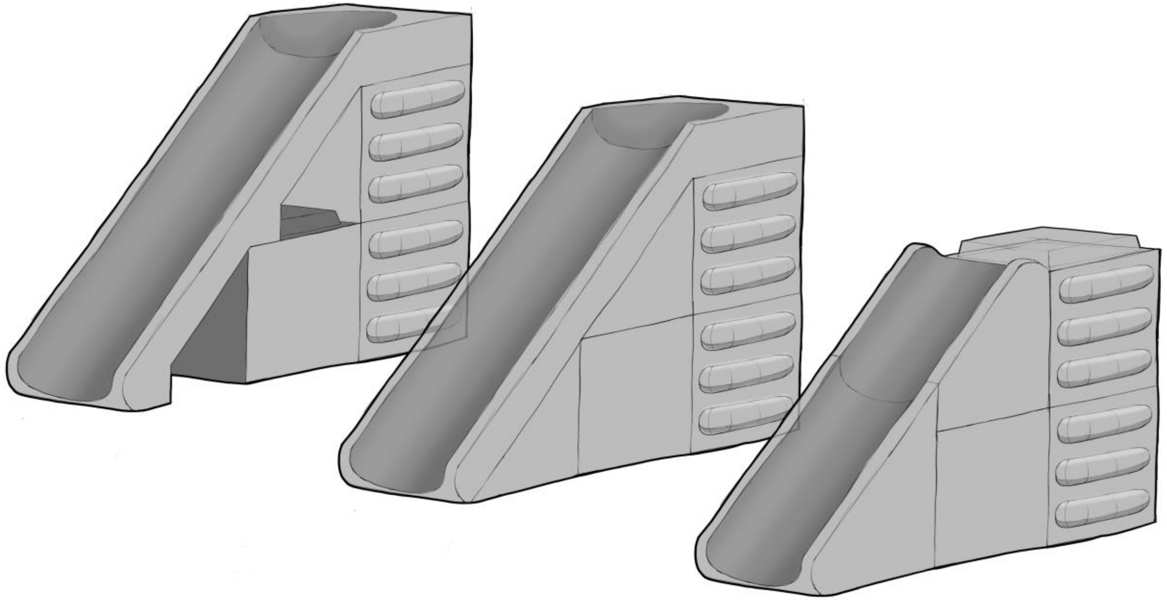


Appendix V

Design sketching of casted Geopolymer structures | Idea 6

The sixth idea elaborates further on stackable blocks with an opening at the bottom. A big difference here is that the openings at the bottom and stud at the top are slanted, which allows for more easy removal from the steel mould. As an interesting exercise I drew several designs for how a sliding element would be placed on top of these blocks.

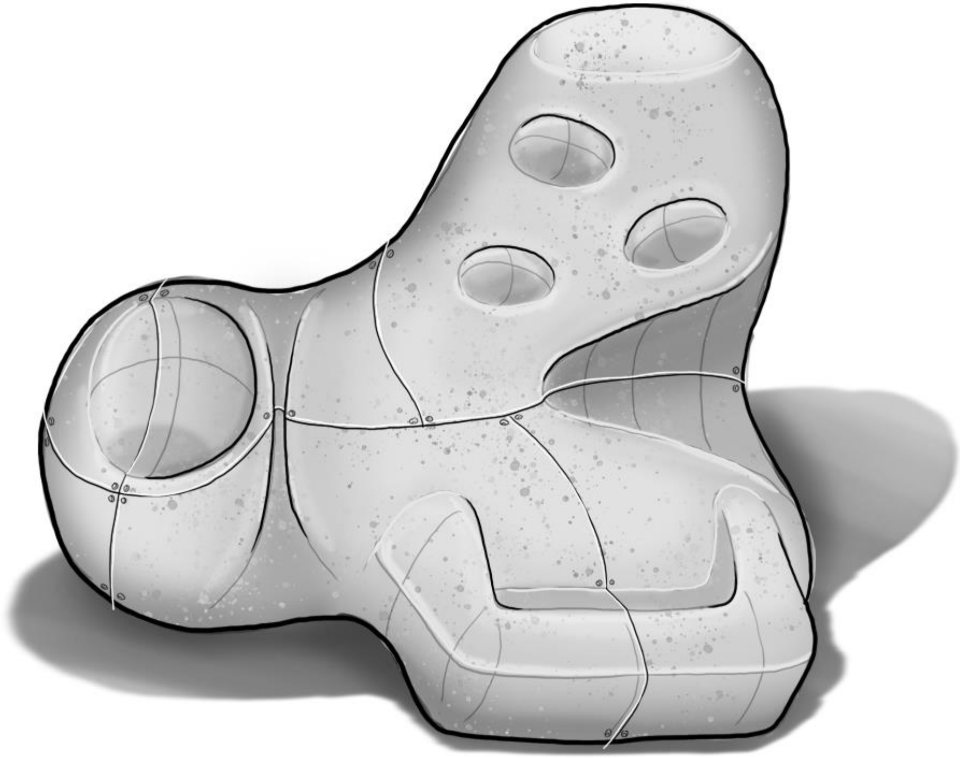


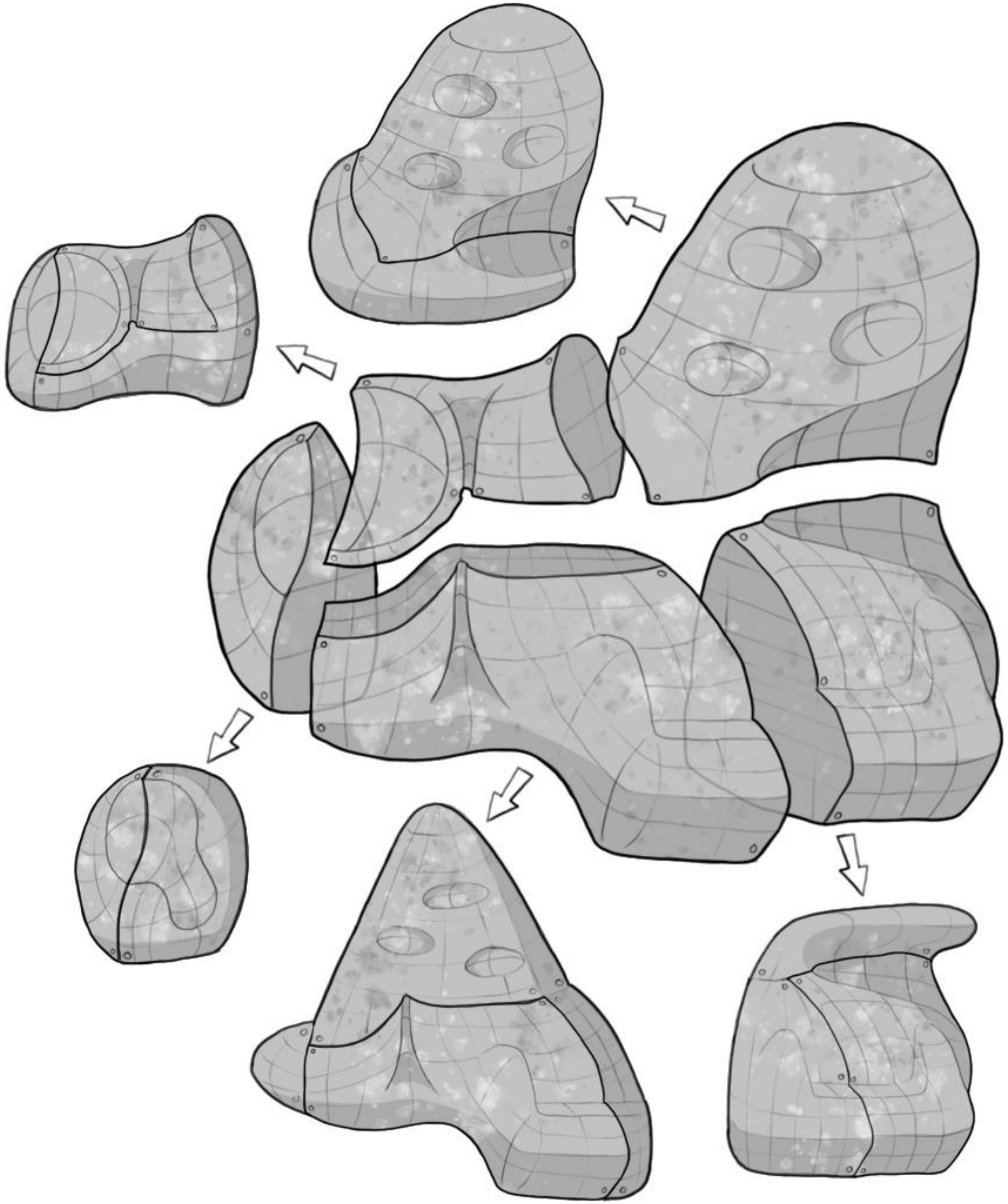


Appendix V

Design sketching of casted Geopolymer structures | Idea 7

For the seventh idea I looked at how to create more round and flowing shapes. Big and Geopolymer 'boulders' can be connected to create unique shapes to climb on or sit in. This concept shares the same problem with concept 5, producing these modules would require a lot of different and complex moulds.

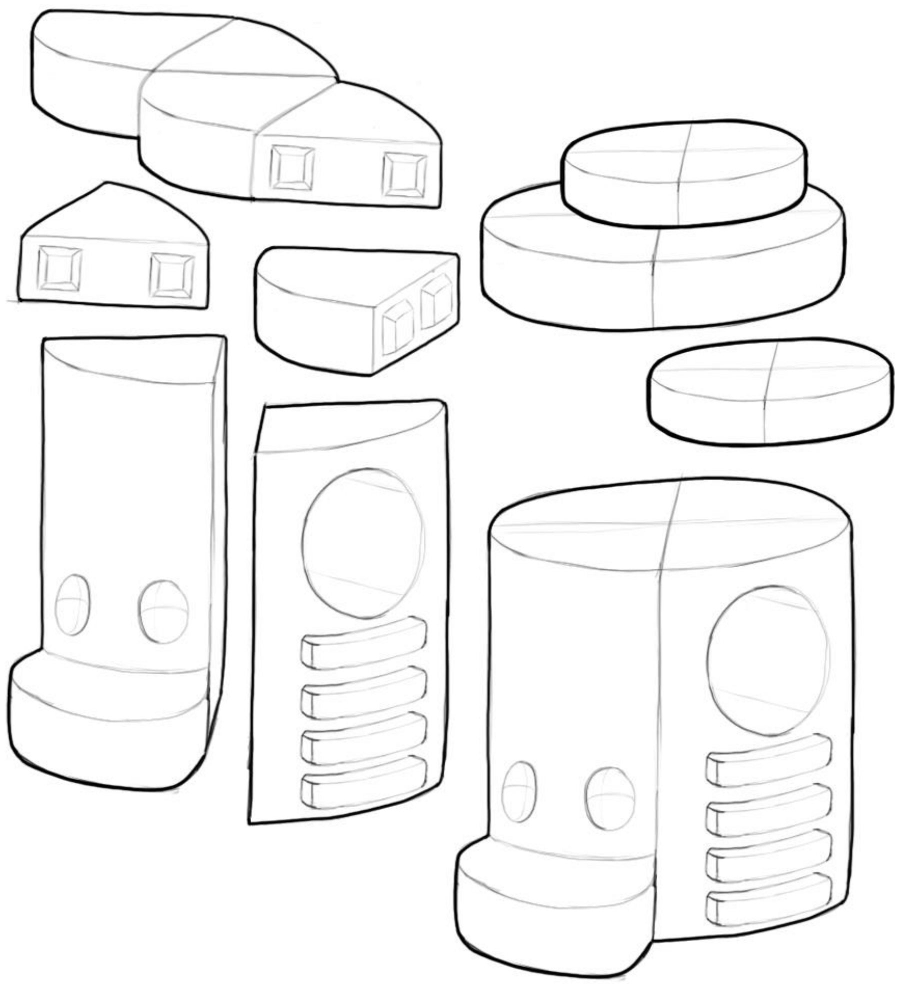


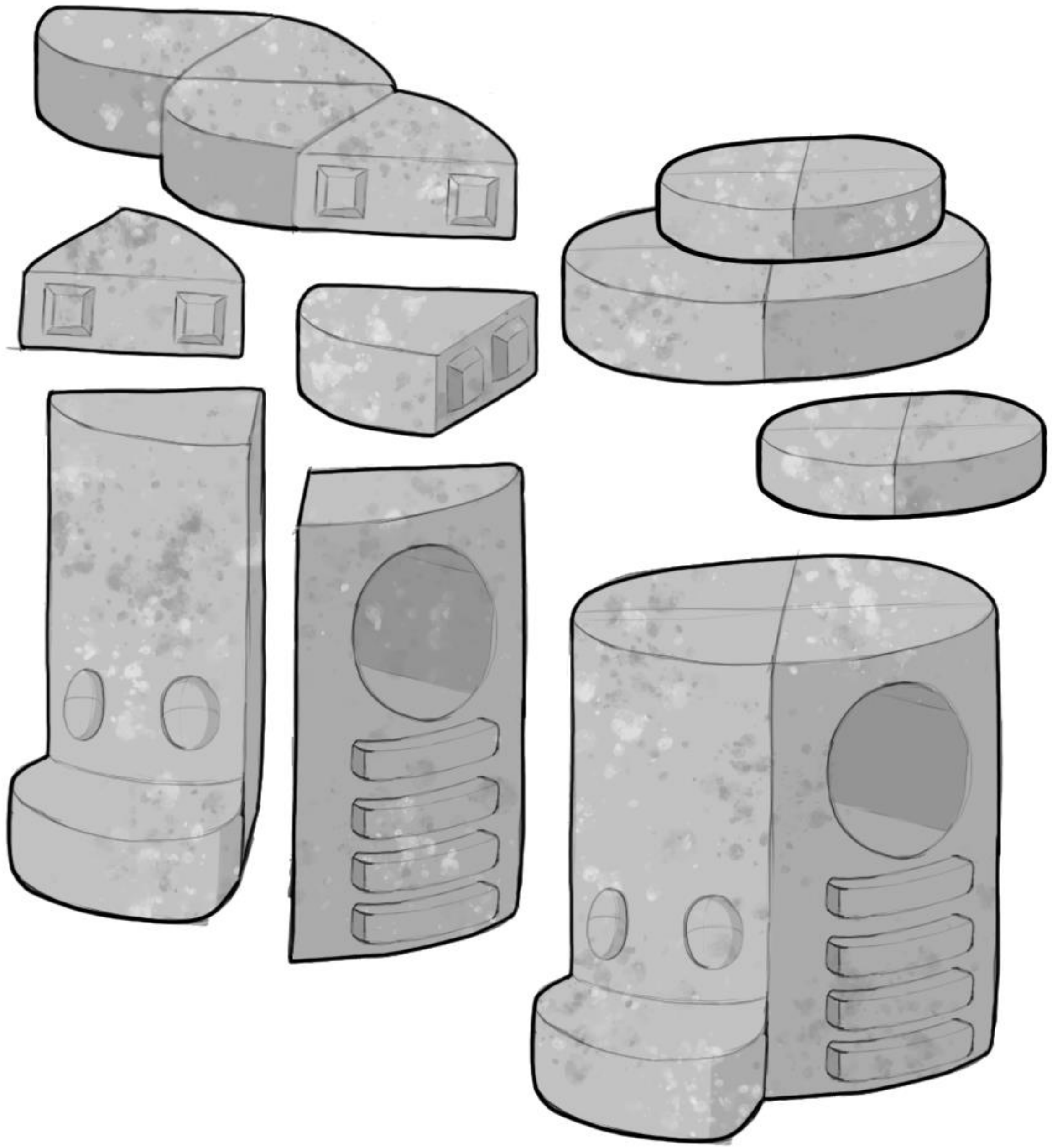


Appendix V

Design sketching of casted Geopolymer structures | Idea 8

The eight idea is a little different. Instead of cubes this playground makes use of quarter circle shapes to create climbing towers, podiums and other interesting play structures.



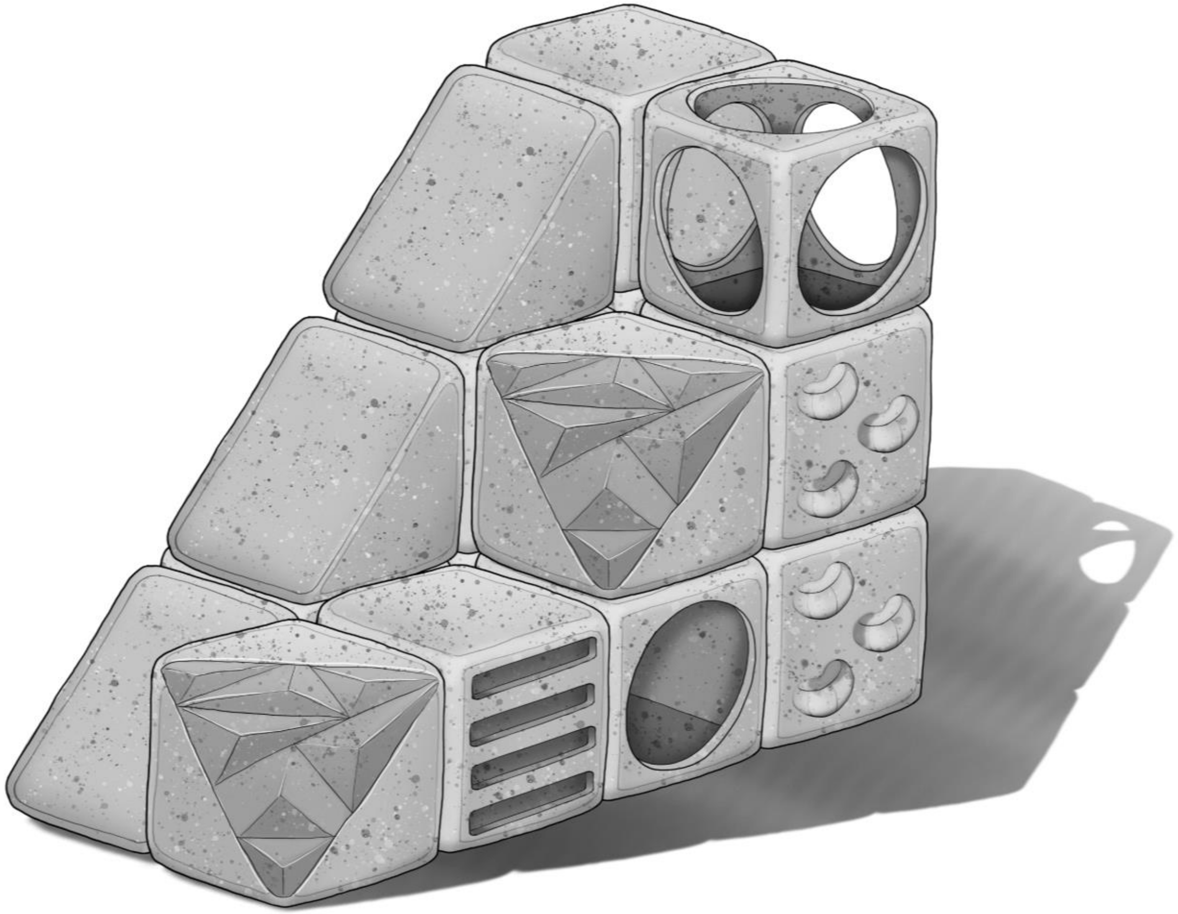


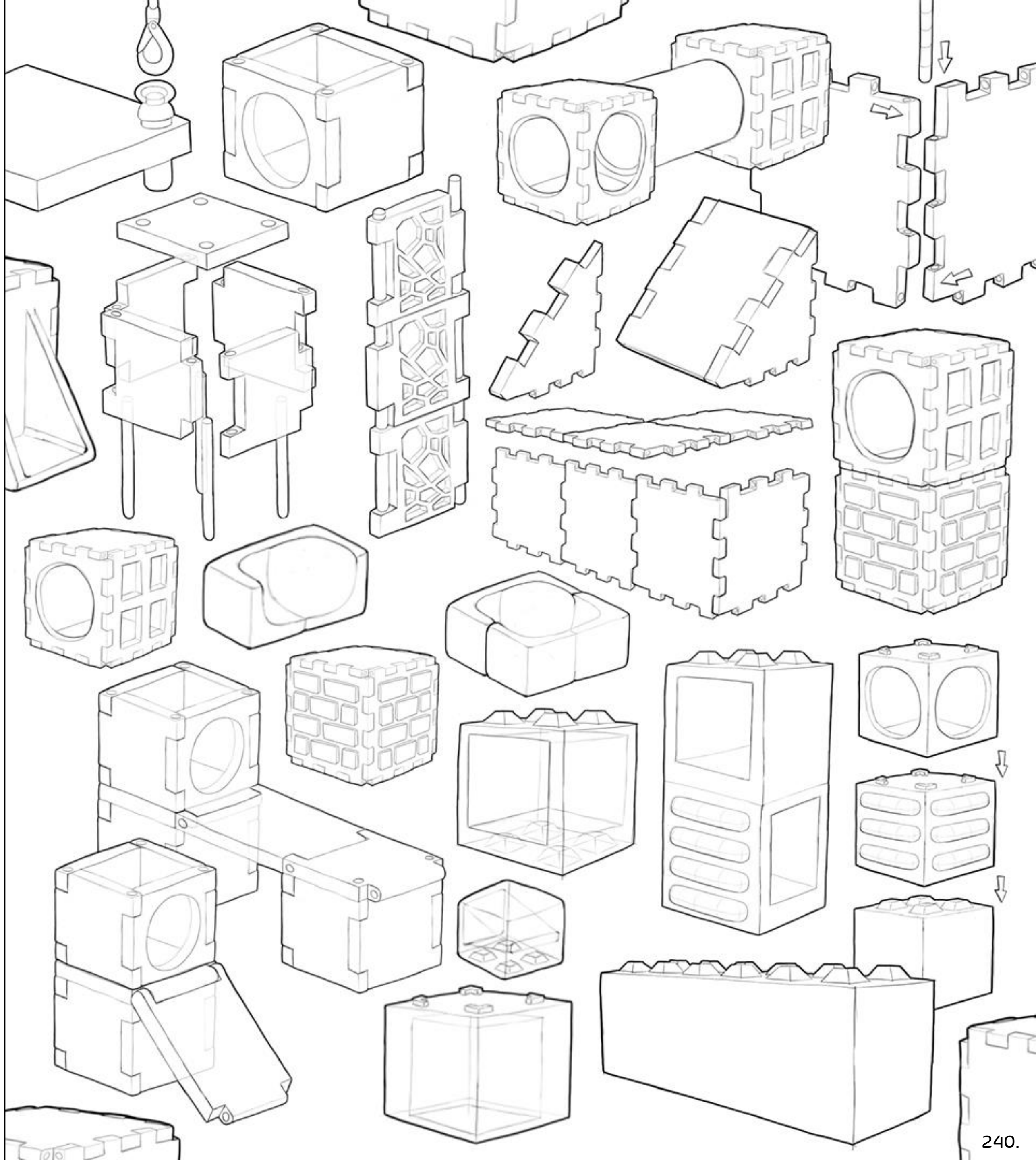
Appendix V

Design sketching of casted Geopolymer structures | Idea 9

The ninth idea combines the Geopolymer cubes with the bamboo poles. Several combinations were drawn out to see what this would look like and what is possible with these two materials. This idea could be combined with any of the other cube ideas to secure or stack them. Again, the cubes can have a different protrusions and indentations to create climbing elements or places to sit or hide in. Sloped elements can be used for sliding or climbing, and a ´messy´ slanted side can look like a side of a mounting which offers another interesting climbing experience.

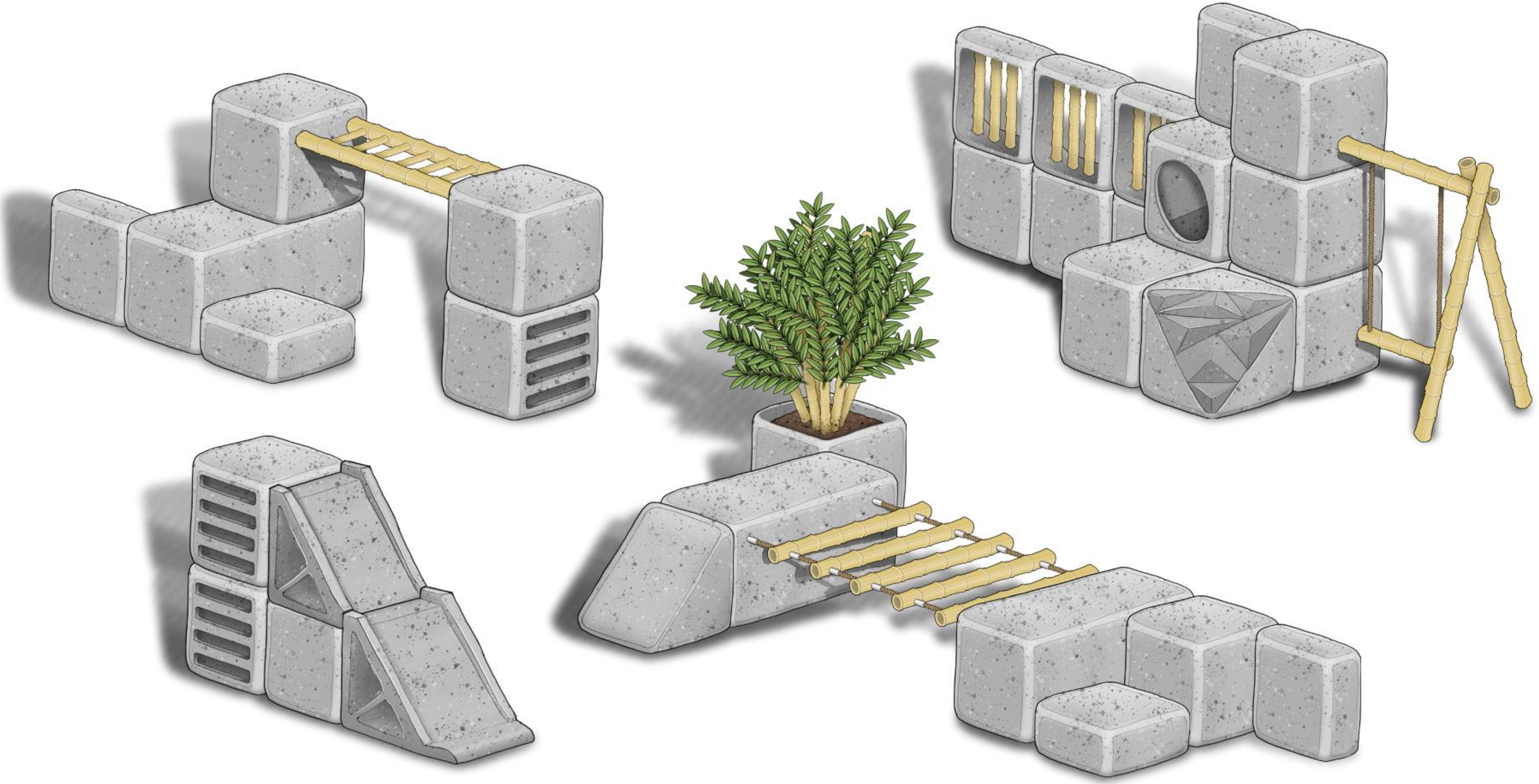
On page 241 you can find a concept of a Geopolymer and bamboo playground with unique play modules.





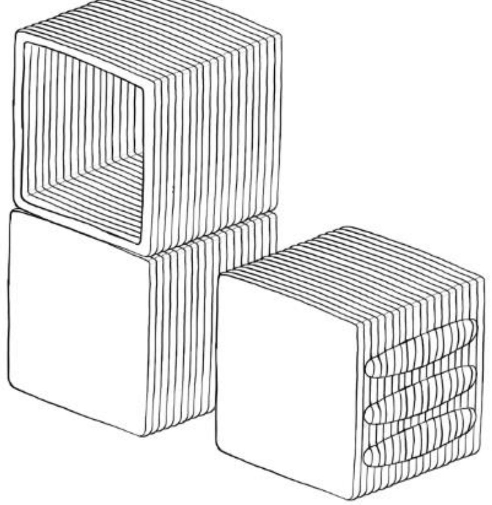
Appendix V

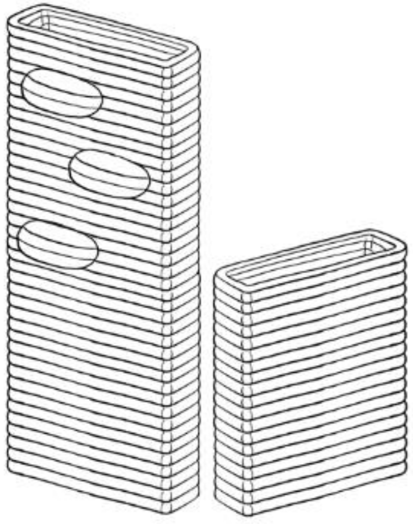
Design sketching of casted Geopolymer structures | Idea 9

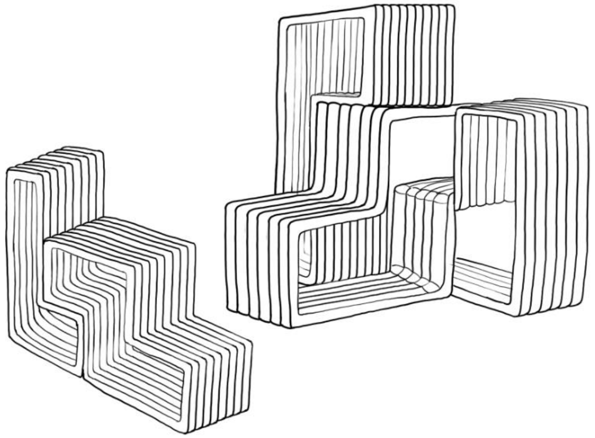


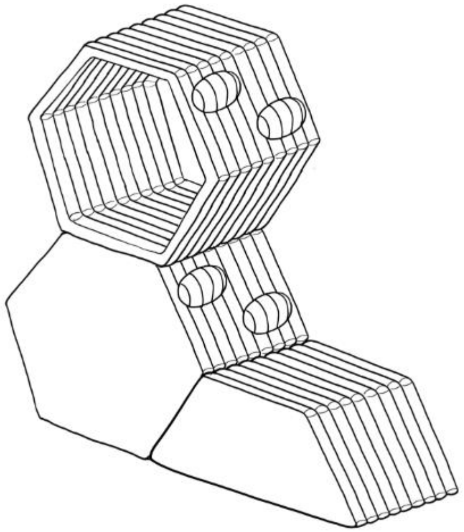
Appendix W

Shape sketches and evaluation based on Harris profile









Shape 1: Cube

Design requirements	- -	-	+	+ +	Explanation
The shapes must be stackable				■	Cube shape allows for stacking
The shapes must be easy to lift and moved with a clamp				■	Cube shape allows for clamping
The shape allows for integrating several play functions			■		Cube has several sides where play elements can be added
The shape allows for integrating a mono-material connection				■	Shapes can be connected with for example a jigsaw connection in multiple directions
The shape can be 3D-printed				■	The shape allows for 3D-printing
The shape allows children to sit in them if hollow				■	Cube shape allows for children to sit in it
A playground made from these shapes looks exciting and fun		■			As all shapes are cubes this might look a bit boring and static
The shape allows for a smooth fit between different modules (all shapes can fit together in some way)				■	The cubes can fit together in a lot of different ways

Shape 2: Panel

Design requirements	- -	-	+	+ +	Explanation
The shapes must be stackable		■			Thin shape does not allow for stacking without the need of additional connectors
The shapes must be easy to lift and moved with a clamp			■		Have to be lifted on the printed side
The shape allows for integrating several play functions		■			Panel only has two sides
The shape allows for integrating a mono-material connection		■			Panels can only be connected in this manner on their narrow side
The shape can be 3D-printed				■	The shape allows for 3D-printing
The shape allows children to sit in them if hollow	■				The shape is too narrow
A playground made from these shapes looks exciting and fun	■				Flat panels are not very exciting looking
The shape allows for a smooth fit between different modules (all shapes can fit together in some way)				■	As the panels are flat, they will fit together smoothly

Shape 3: Tetris

Design requirements	- -	-	+	+ +	Explanation
The shapes must be stackable				■	Tetris shapes allow for stackability in multiple directions
The shapes must be easy to lift and moved with a clamp				■	The modules can be lifted with a clamp as it has two flat sides
The shape allows for integrating several play functions				■	The shapes have many sides to which play elements can be added. The different shapes, such as the Z block, allow for extra play abilities
The shape allows for integrating a mono-material connection			■		Shapes can be connected with for example a jigsaw connection. Though, this only works in one direction. However, the shapes hold each other in place as well
The shape can be 3D-printed				■	The shape allows for 3D-printing
The shape allows children to sit in them if hollow			■		This is dependent of the shape. Not all shapes will allow for this
A playground made from these shapes looks exciting and fun				■	As the shapes can be configured in a lot of interesting ways, this will create an exciting playground. They also encourage to climb on them
The shape allows for a smooth fit between different modules (all shapes can fit together in some way)				■	The Tetris shapes can fit together in a lot of different ways, and in multiple directions

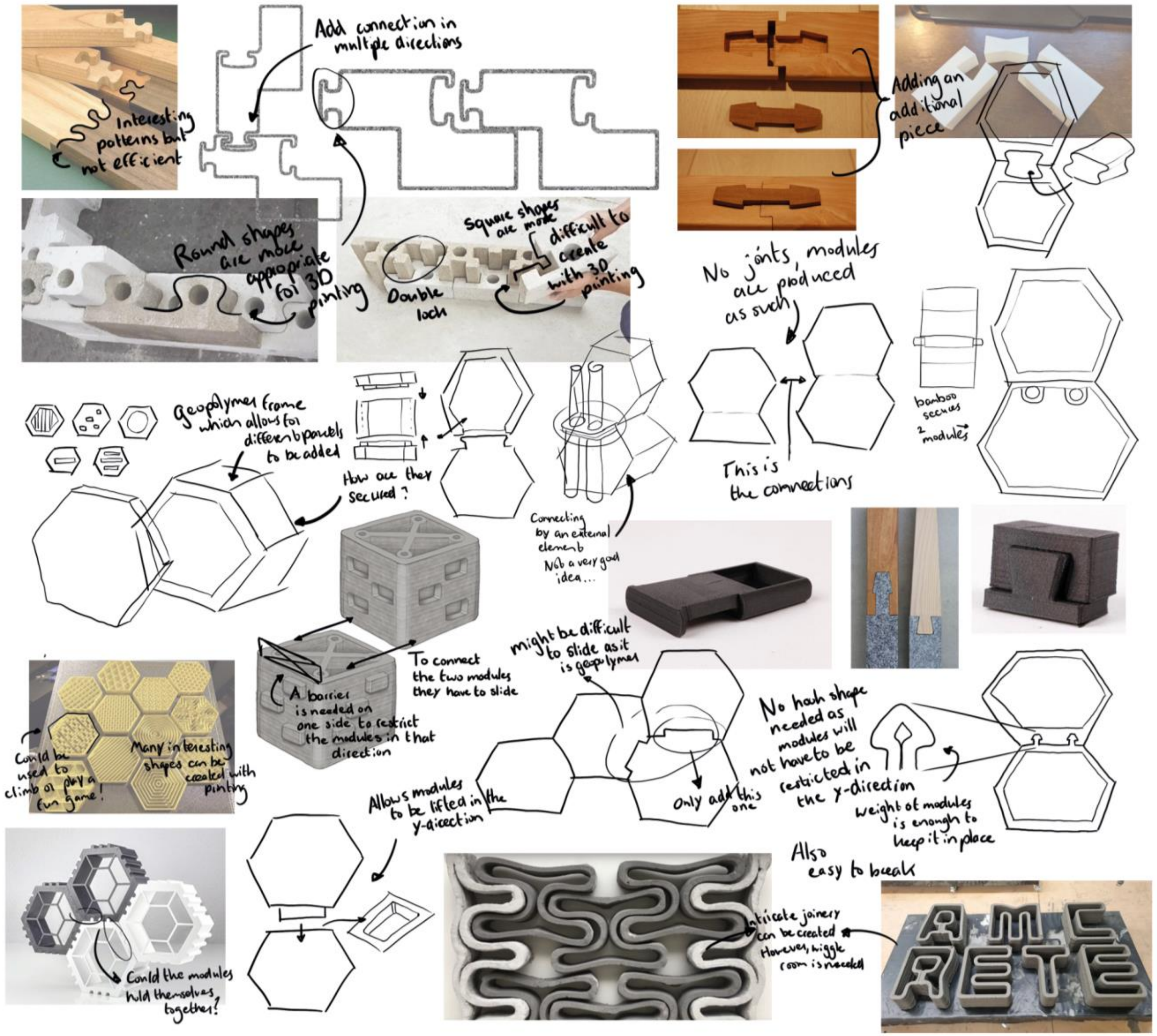
Shape 4: Hexagon

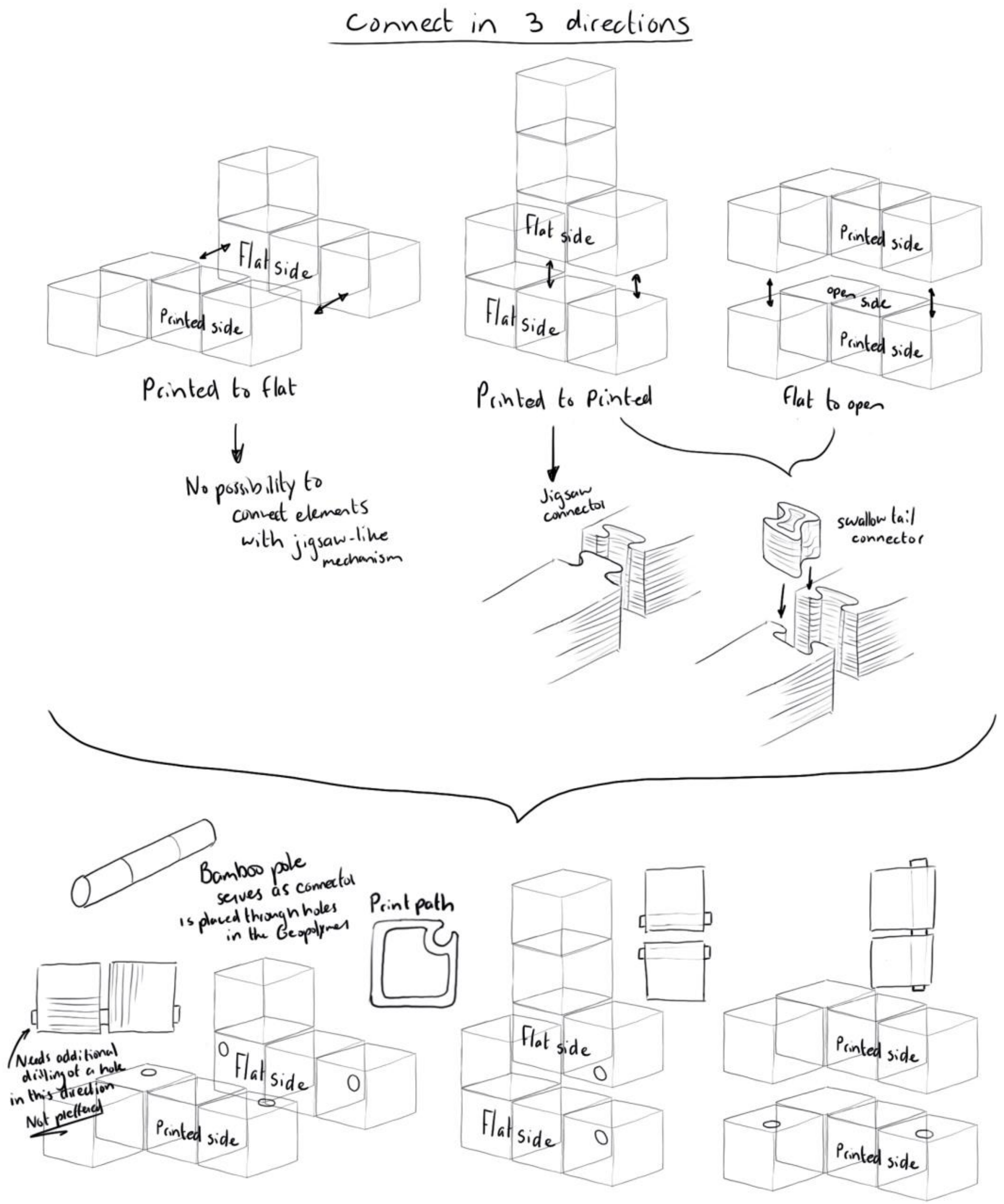
Design requirements	- -	-	+	+ +	Explanation
The shapes must be stackable			■		Shape can be stacked but the slanted sides make this more difficult
The shapes must be easy to lift and moved with a clamp			■		Flat sides allow for lifting, but the slanted can not be lifted with a clamp
The shape allows for integrating several play functions				■	Hexagon has many sides where play elements can be added. The slanted side also allows for additional play abilities
The shape allows for integrating a mono-material connection			■		Shapes can be connected in only one direction with a jigsaw connection
The shape can be 3D-printed				■	The shape allows for 3D-printing
The shape allows children to sit in them if hollow				■	Hexagon shape allows for children to sit in it
A playground made from these shapes looks exciting and fun				■	The hexagon shapes make it very playful and encourages to climb on them
The shape allows for a smooth fit between different modules (all shapes can fit together in some way)			■		The shapes fit together, but only in one direction

Appendix X

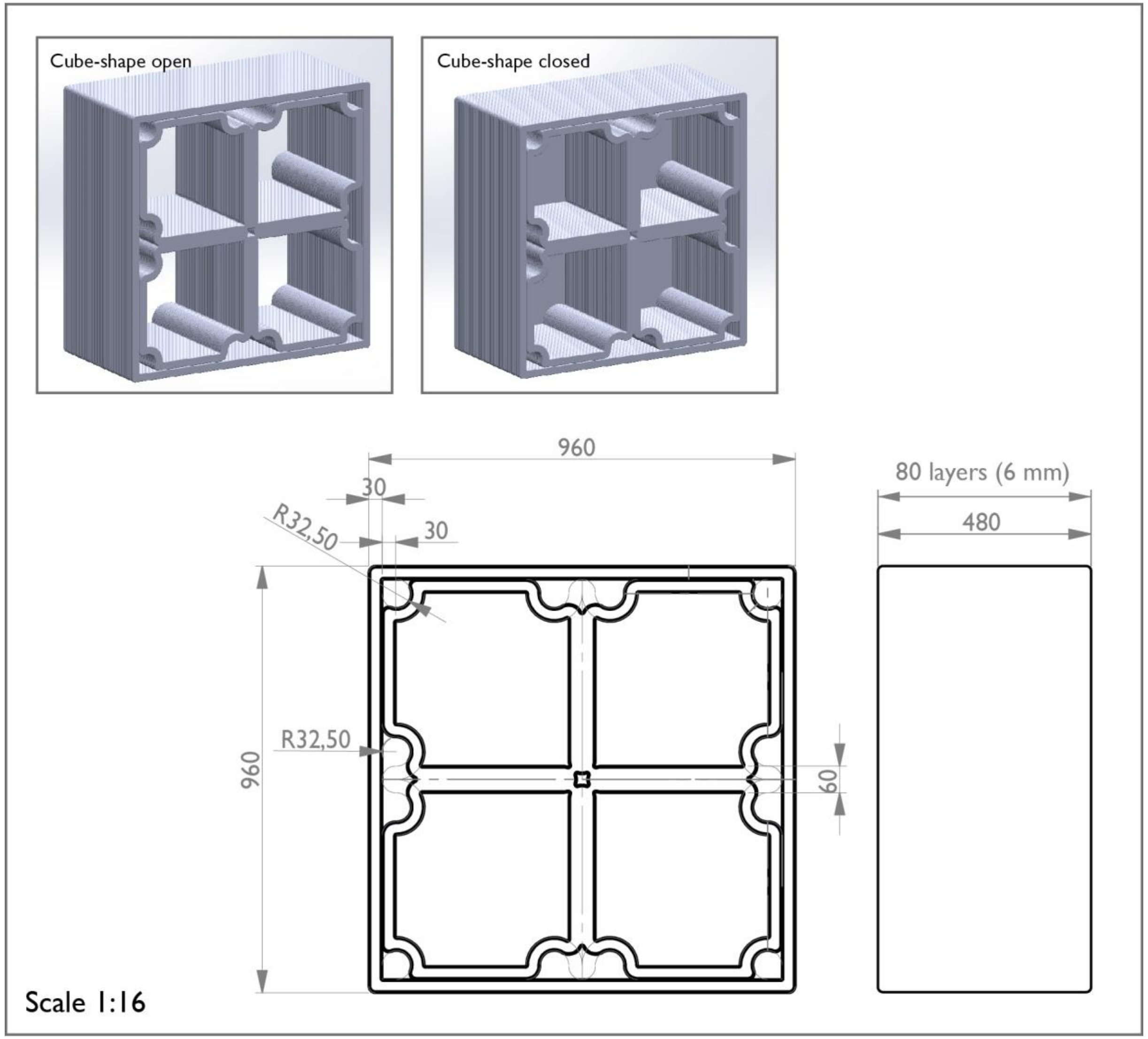
Connections between Geopolymer modules

As the design process is not linear, the study on mono-material connections is partly based on the hexagon shapes, even though I eventually chose the Tetris shapes. However, this is not a problem as the mechanisms of the connections are the same for both shapes.

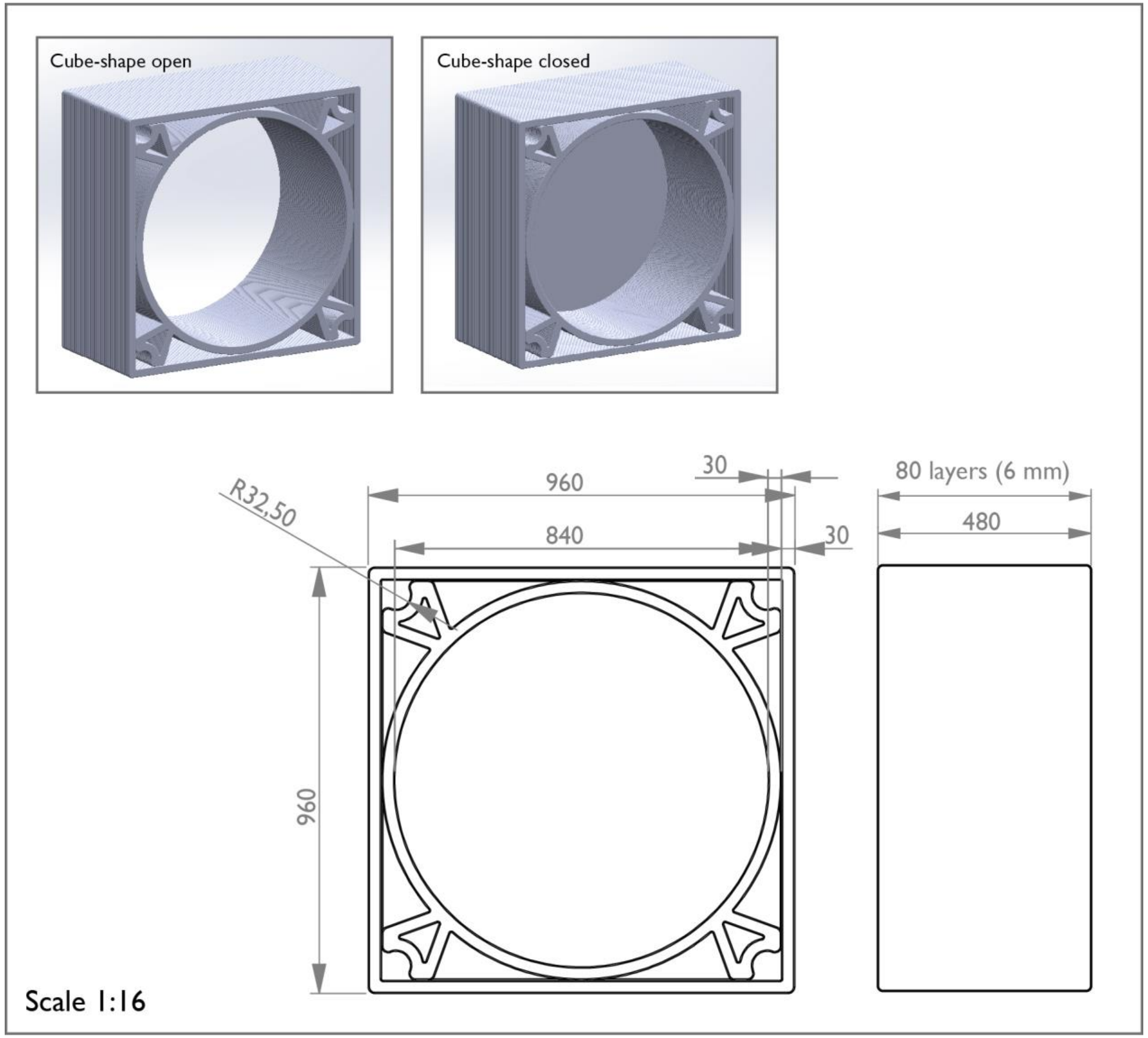




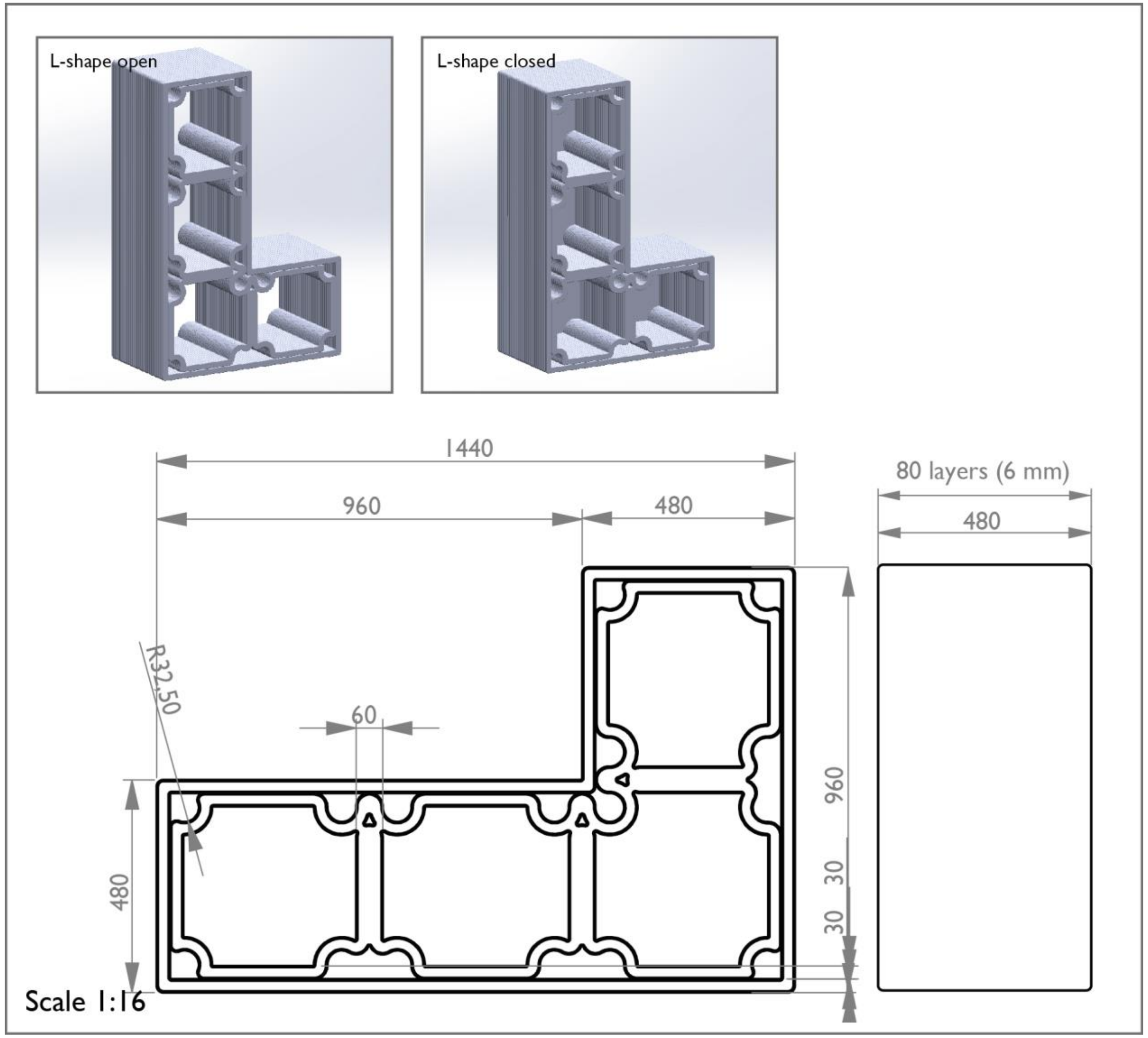
Cube-shape open & closed - with internal ribs (mm)



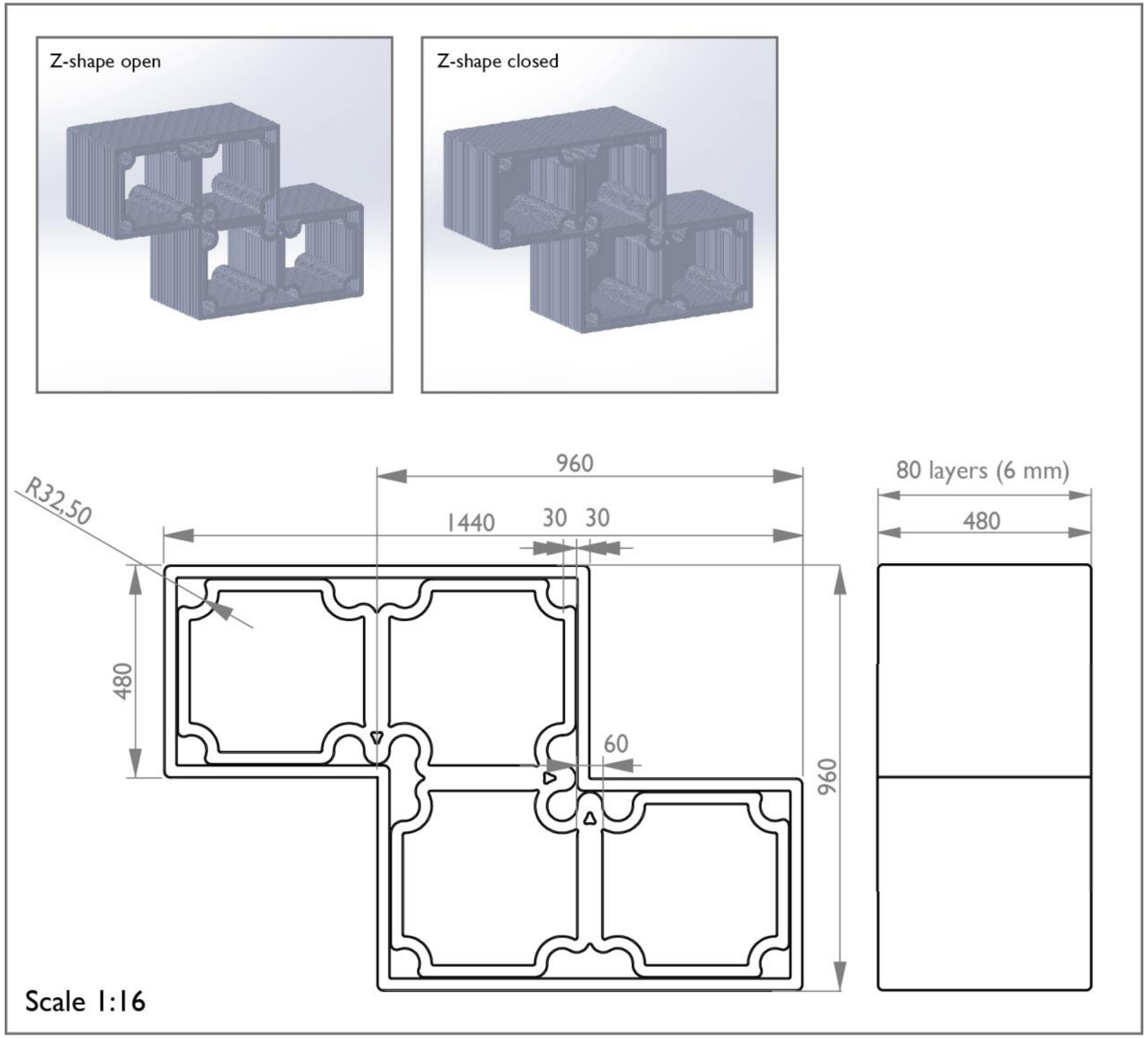
Cube-shape open & closed - with internal tube (mm)



L-shape open & closed (mm)

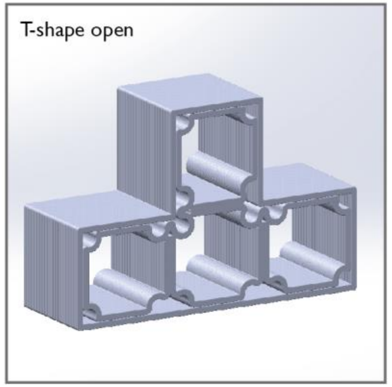


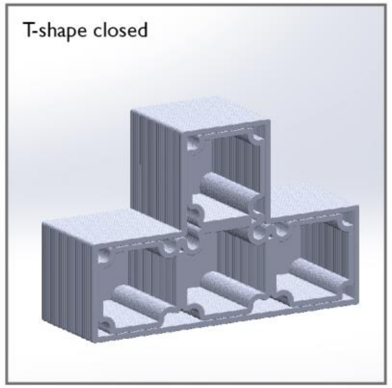
Z-shape open & closed (mm)

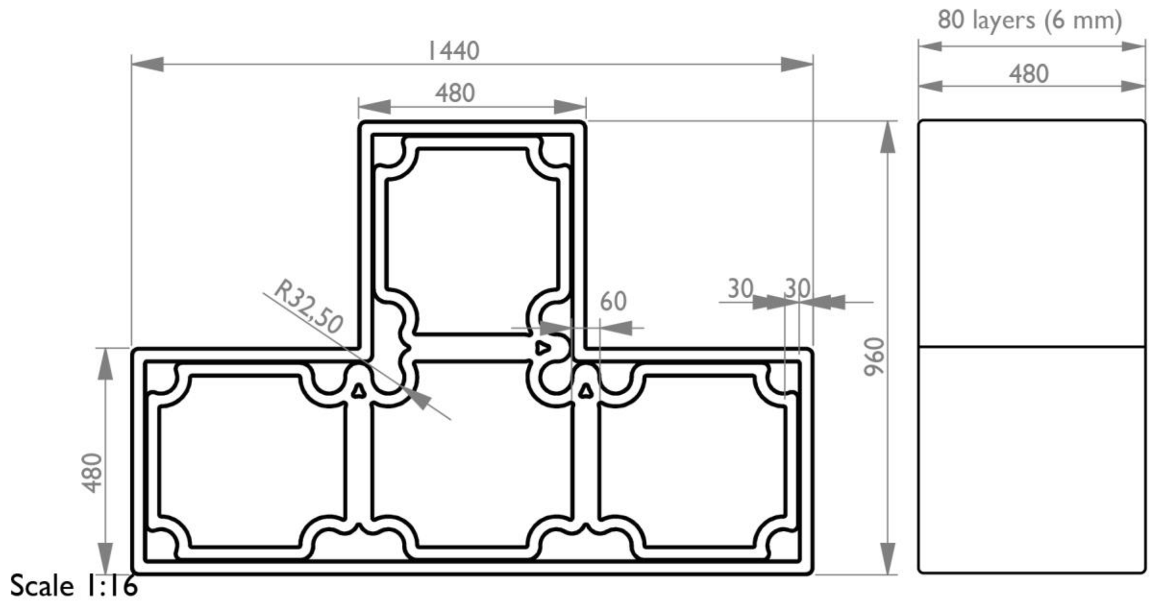


Technical drawings all Blocks

T-shape open & closed (mm)

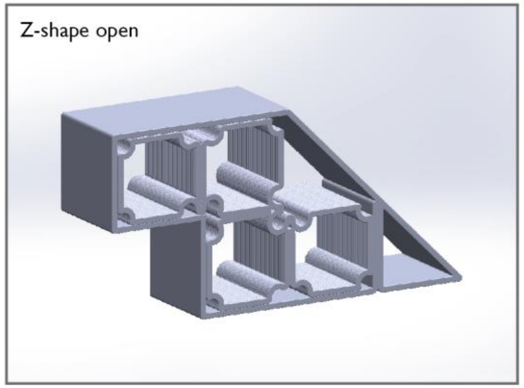


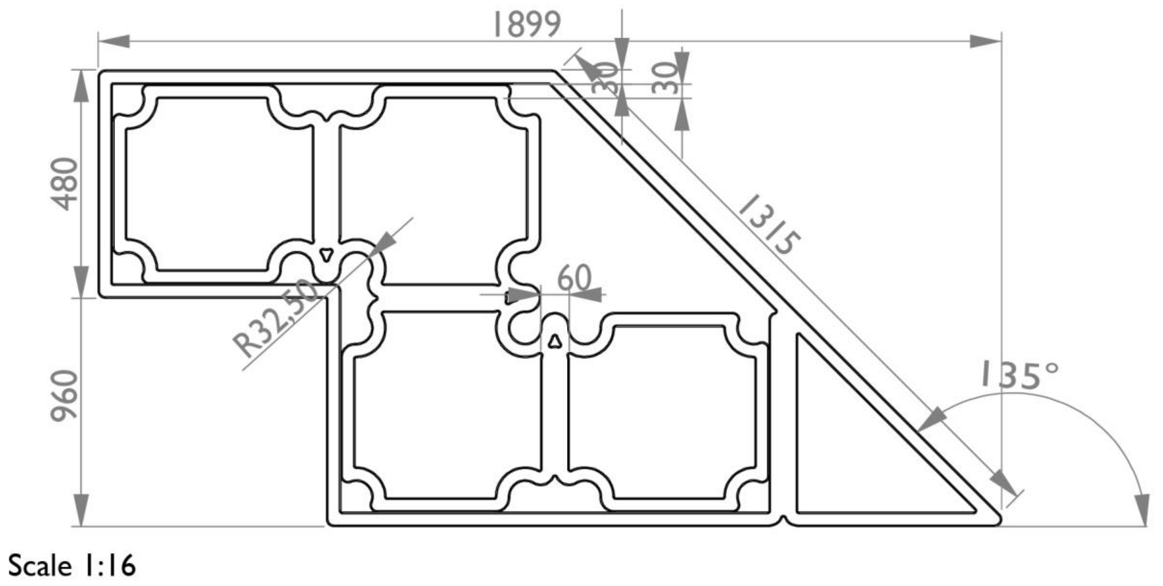




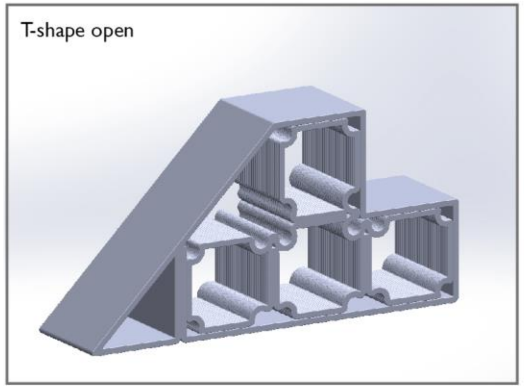
Technical drawings all Blocks

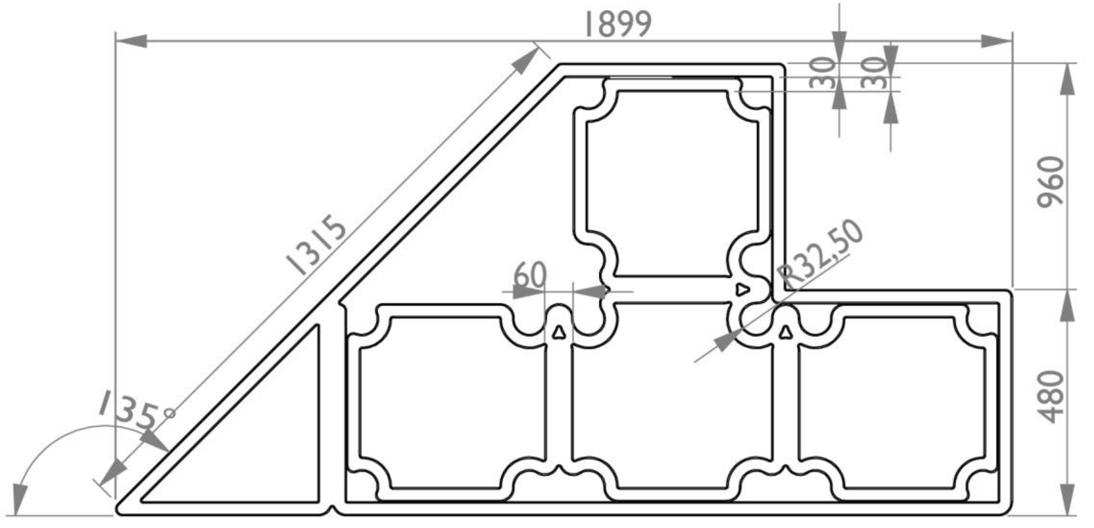
Z-shape open - smooth and sloped (mm)





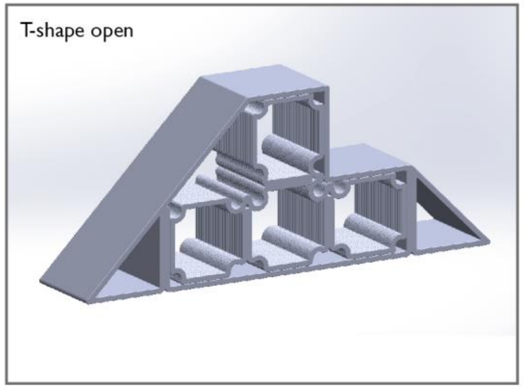
T-shape open - smooth and sloped - one side (mm)

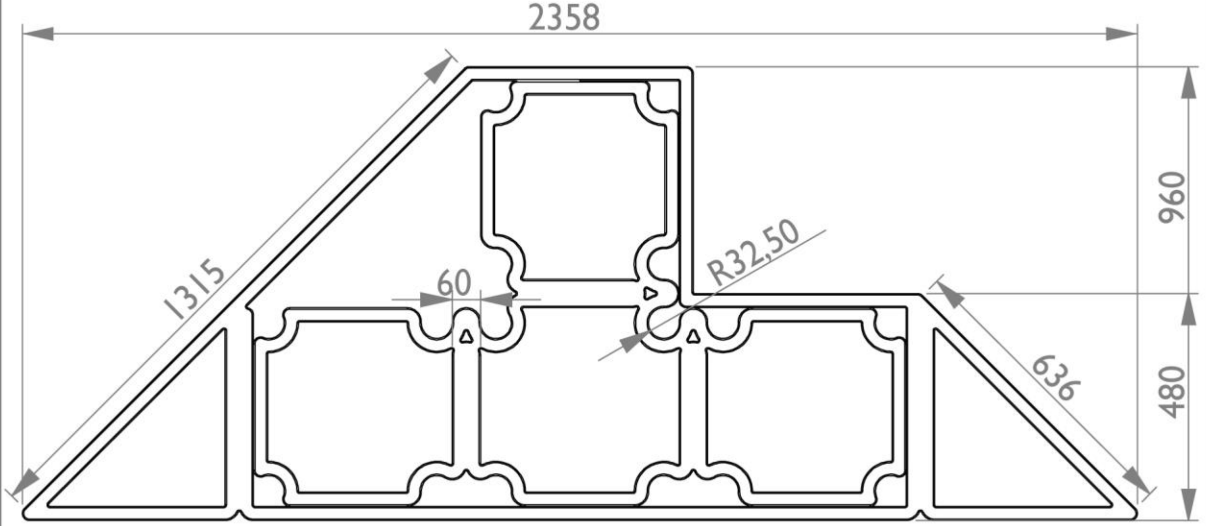




Scale 1:16

T-shape open - smooth and sloped - two sides (mm)





Scale 1:16

Appendix Z

Study on climbing

Appendix AA

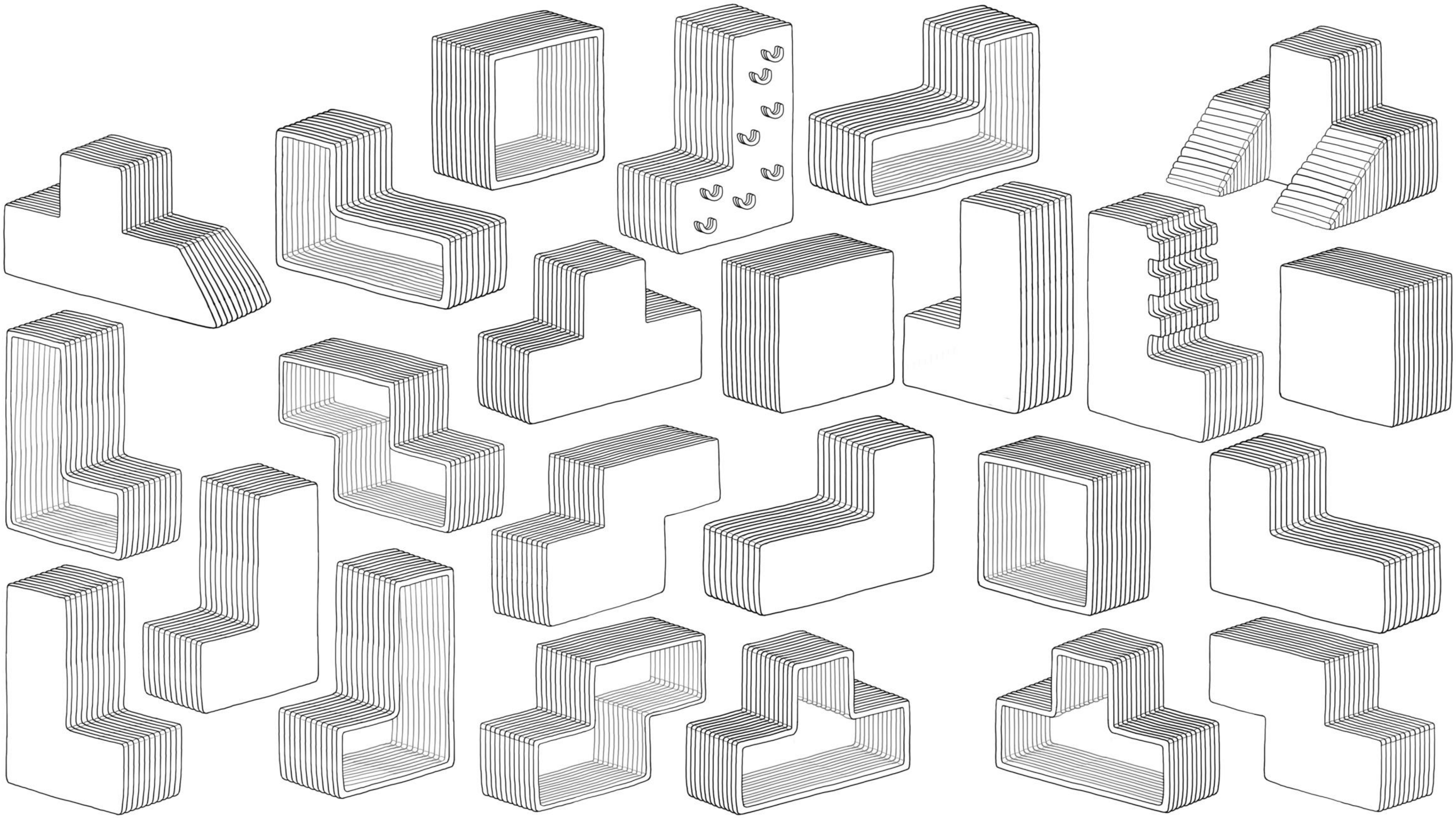
Study on swinging and swaying

Appendix BB

Study on (roller) skating and BMX

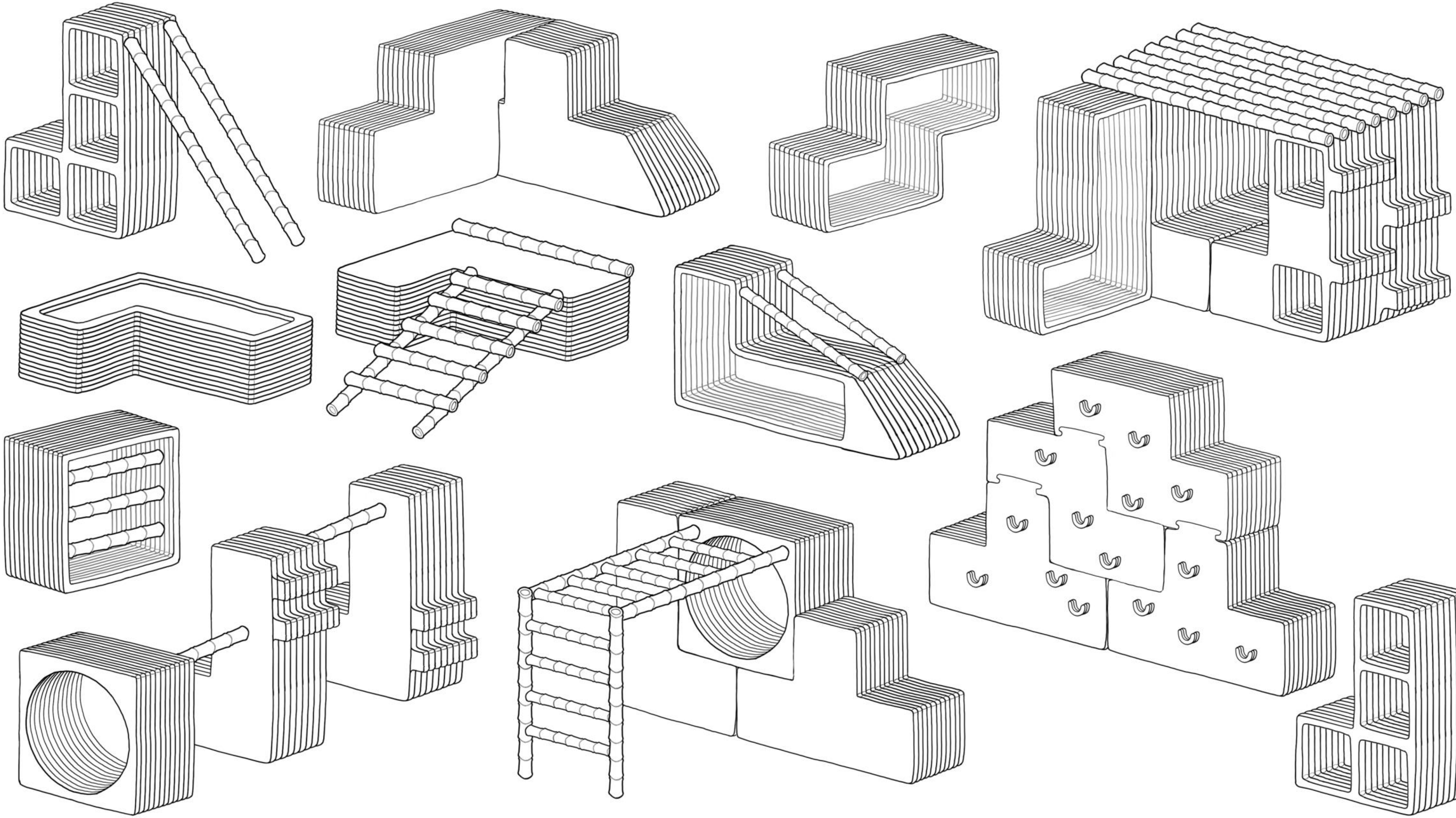
Appendix CC

Design sketching of 3D-printed Tetris Geopolymer play modules

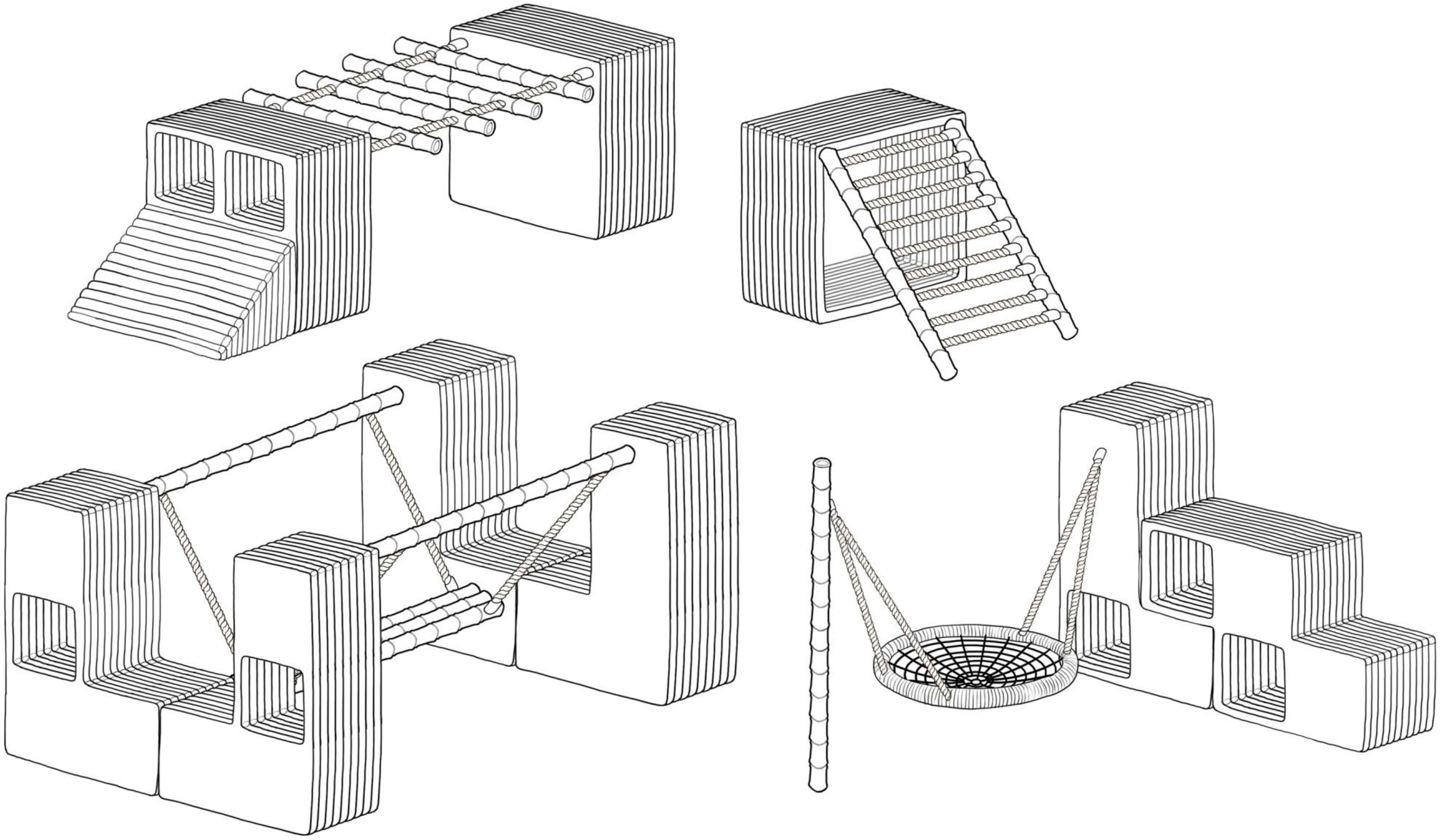


Appendix CC

Design sketching of 3D-printed Tetris Geopolymer play modules

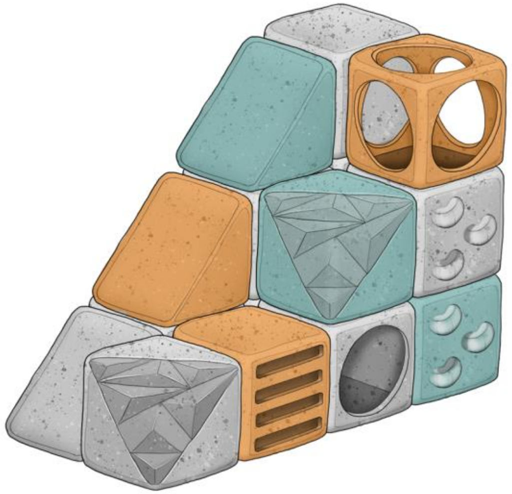


Design sketching of 3D-printed Tetris Geopolymer play modules

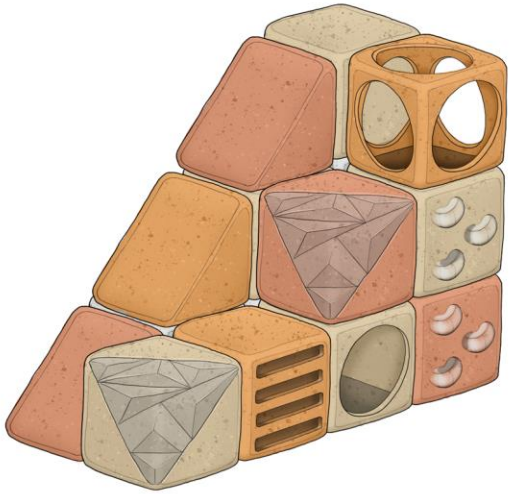


Appendix DD

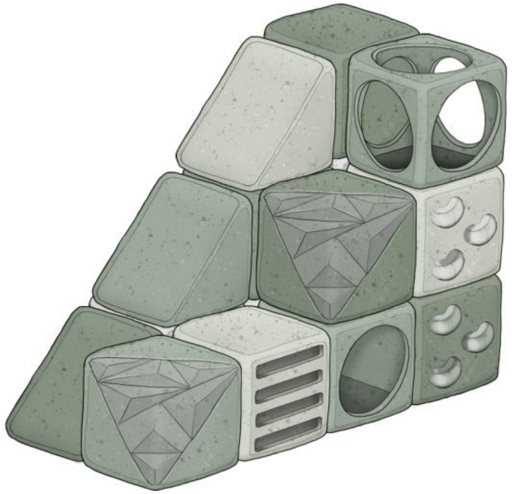
Inspiration board | Colour wheel study



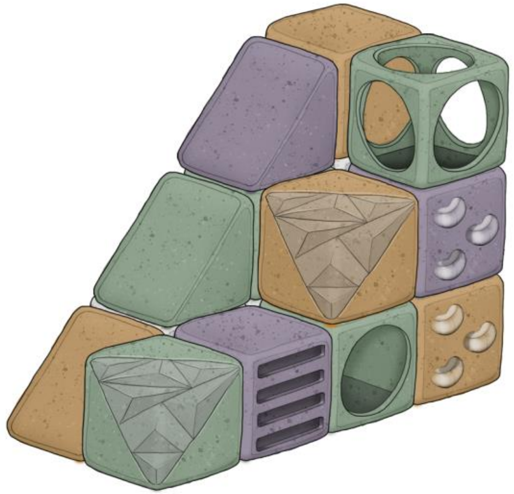
Complementary



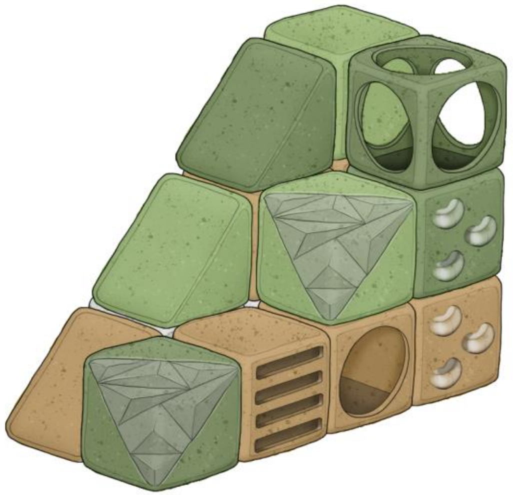
Analogue



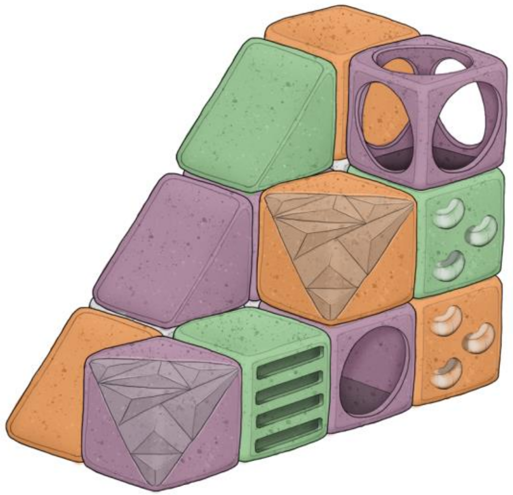
Analogue



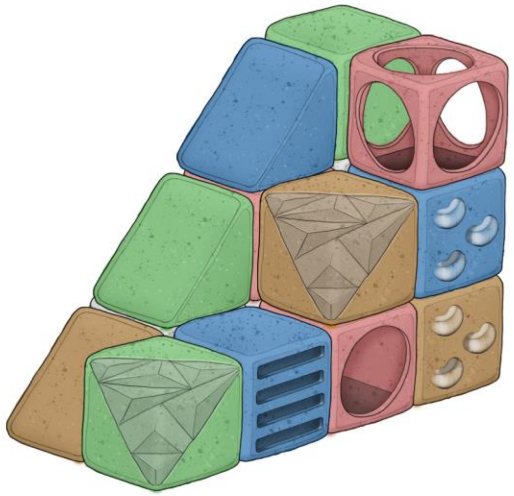
Triadic



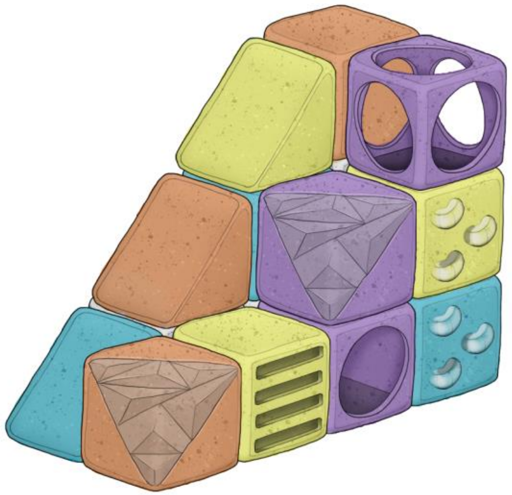
Complementary



Split-complementary

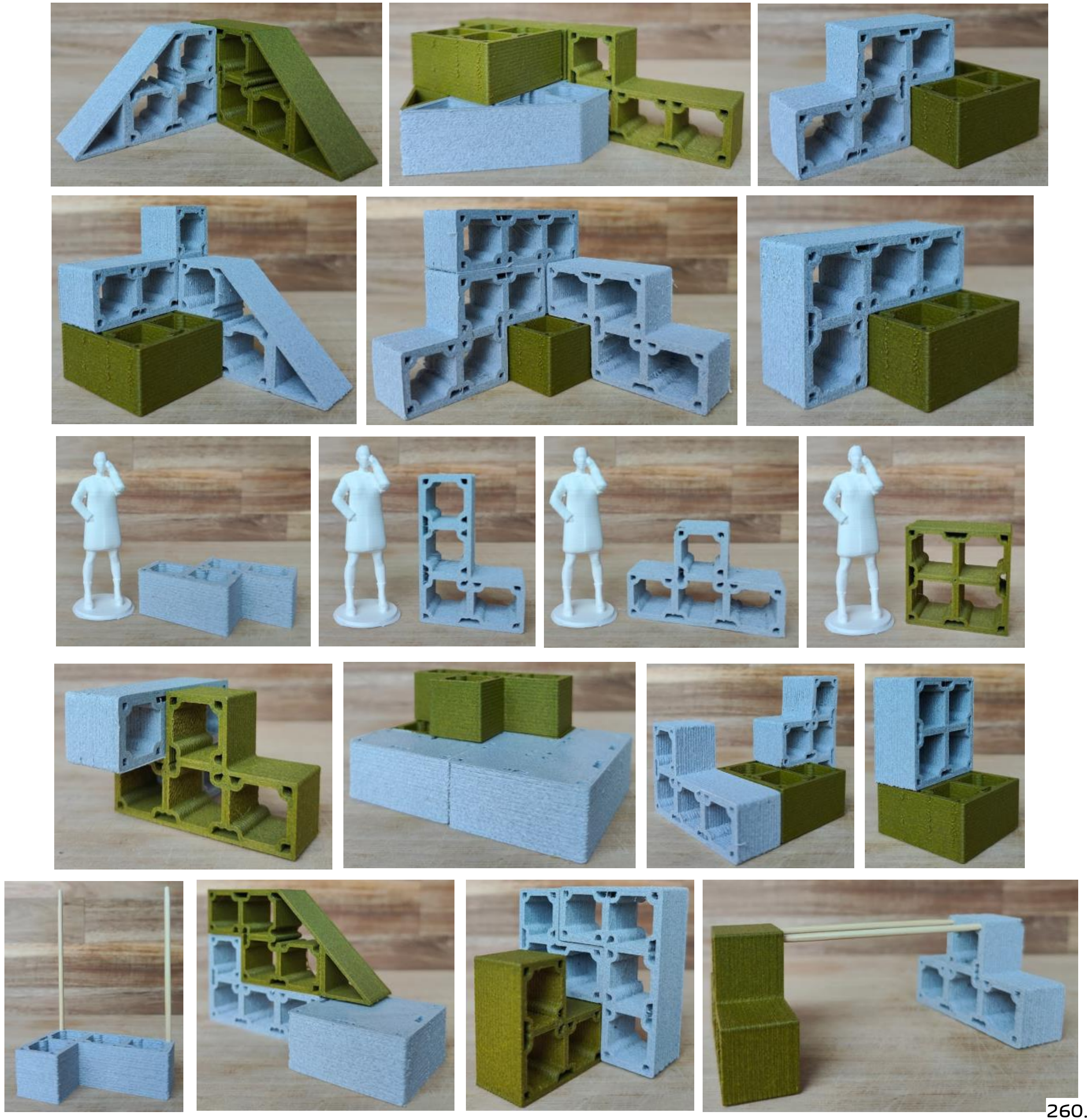


Double split-complementary

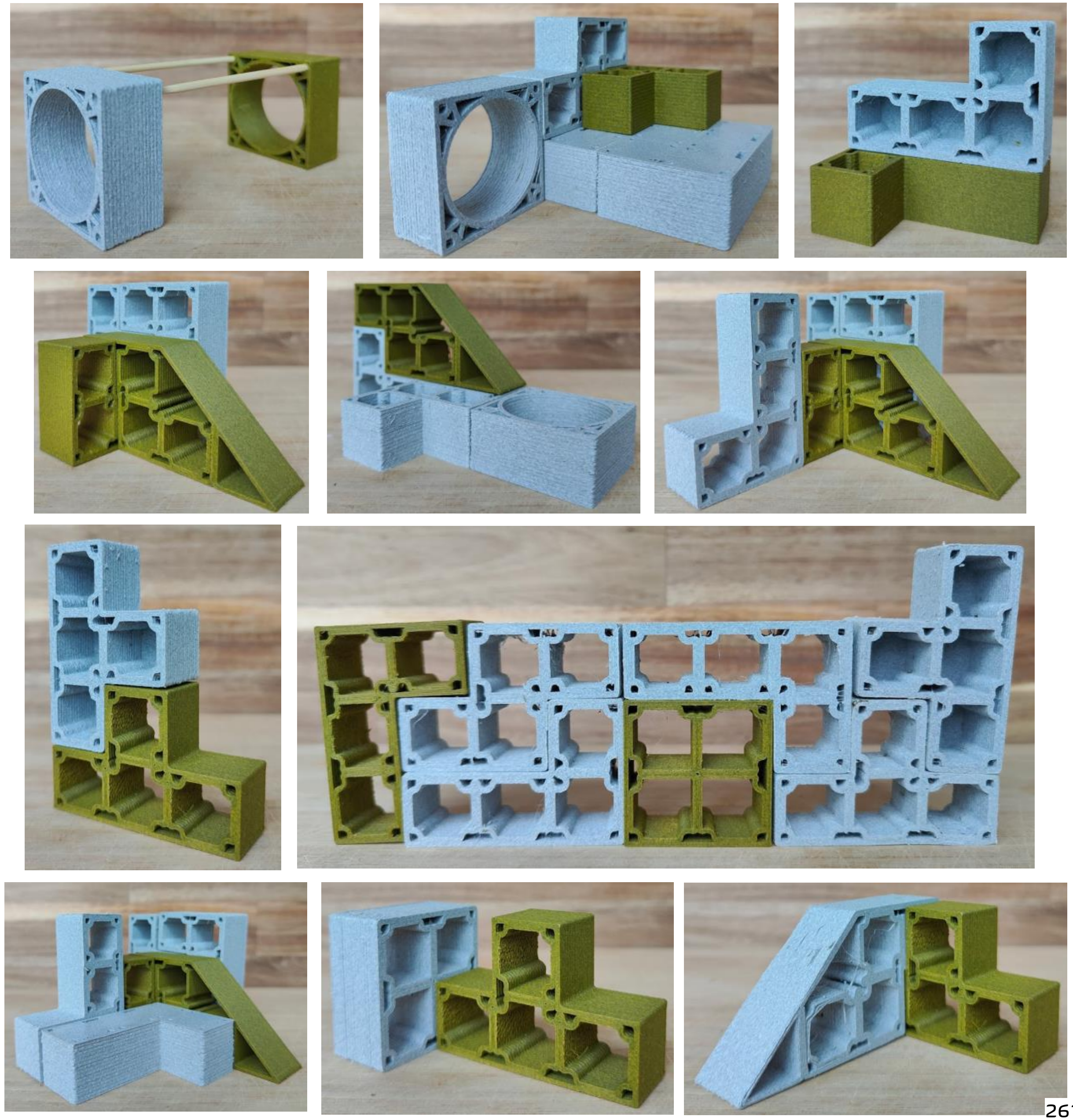


Square

3D-printed scale model Geobam Play Block configurations

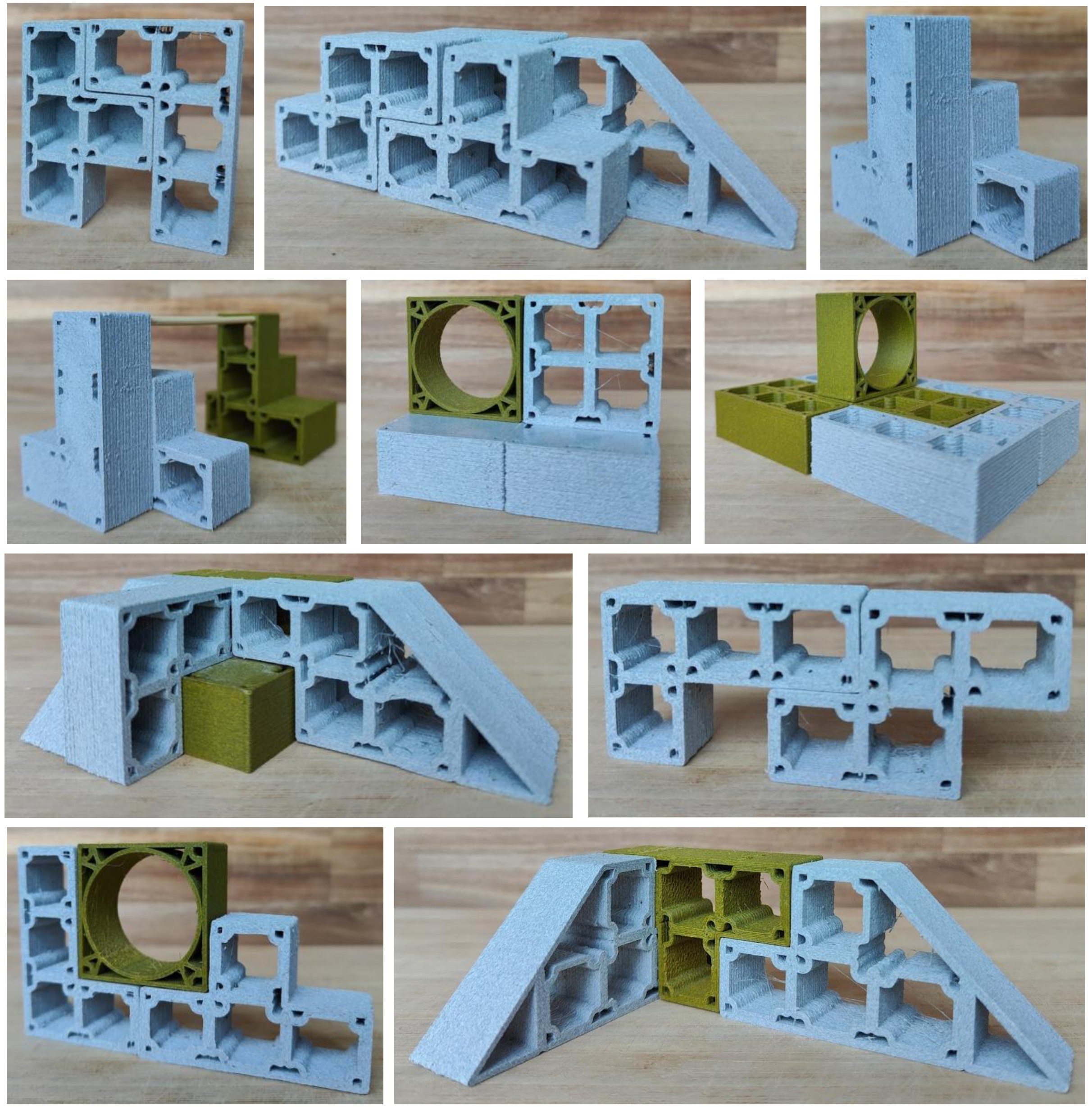


3D-printed scale model Geobam Play Block configurations



Appendix EE

3D-printed scale model Geobam Play Block configurations

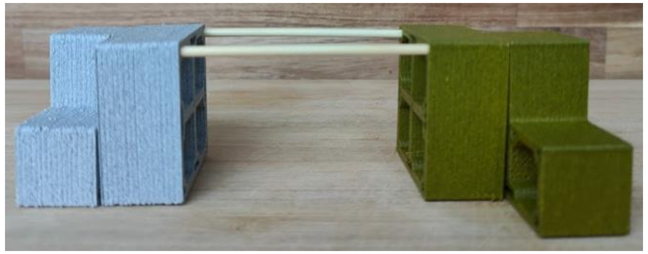
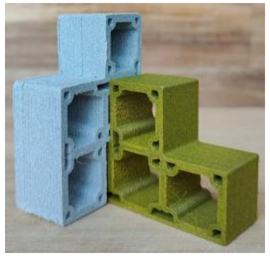
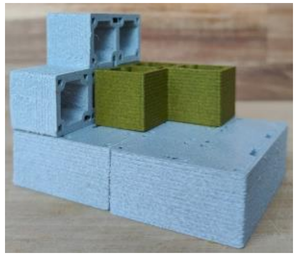
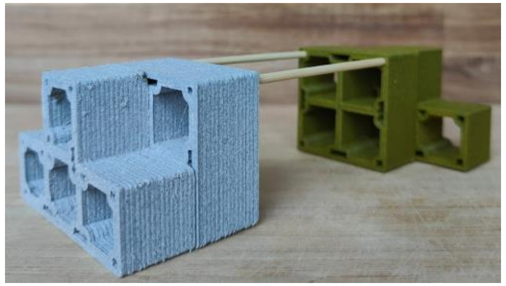


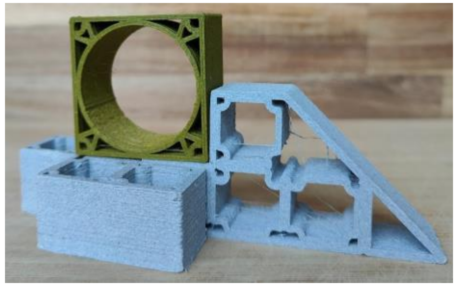
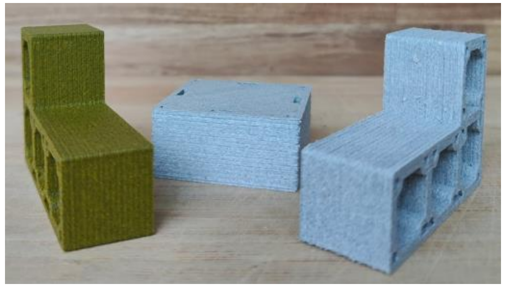
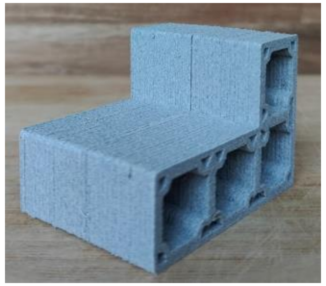
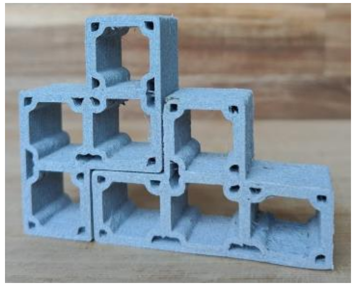
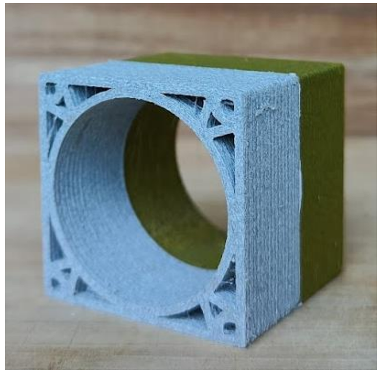
Appendix EE

3D-printed scale model Geobam Play Block configurations

Appendix EE

3D-printed scale model Geobam Play Block configurations

Appendix EE

3D-printed scale model Geobam Play Block configurations