CONCRETE

Concrete in an AM process

Freeform concrete processing

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Master (MSc) thesis

Concrete in an AM process - Freeform concrete processing

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Preface

This graduation thesis has been written to obtain the title of engineer (ir.) at the Delft University of Technology at the Faculty of Architecture and the Built Environment. The Building Technology master track consisted of, next to the graduation project, several design and theoretical courses about building technology. Because of my technical preferences I decided to broaden my horizon by choosing additive manufacturing of concrete as my graduation subject. While the project progressed it became clear that material, production technique and products are very related. The initial challenge of how and what kind of concrete products should be made to use additive manufacturing in a beneficial way changed to how AM should be used to be able to process concrete keeping its beneficial characteristics. This interdisciplinary approach created my role in the middle of the mechanical experts and the architects.
Comparing one and a half year of aerospace engineering to five and a half year architectural education, where I always tried, if I had the chance, to be on the technical side, I realise that my role is between those two extremes. The idea to work at that place increasingly appeals to me.
I want to thank my family, friends, colleagues and mentors Ulrich, Joris and Marcel for the support during my study and graduation.

Dennis

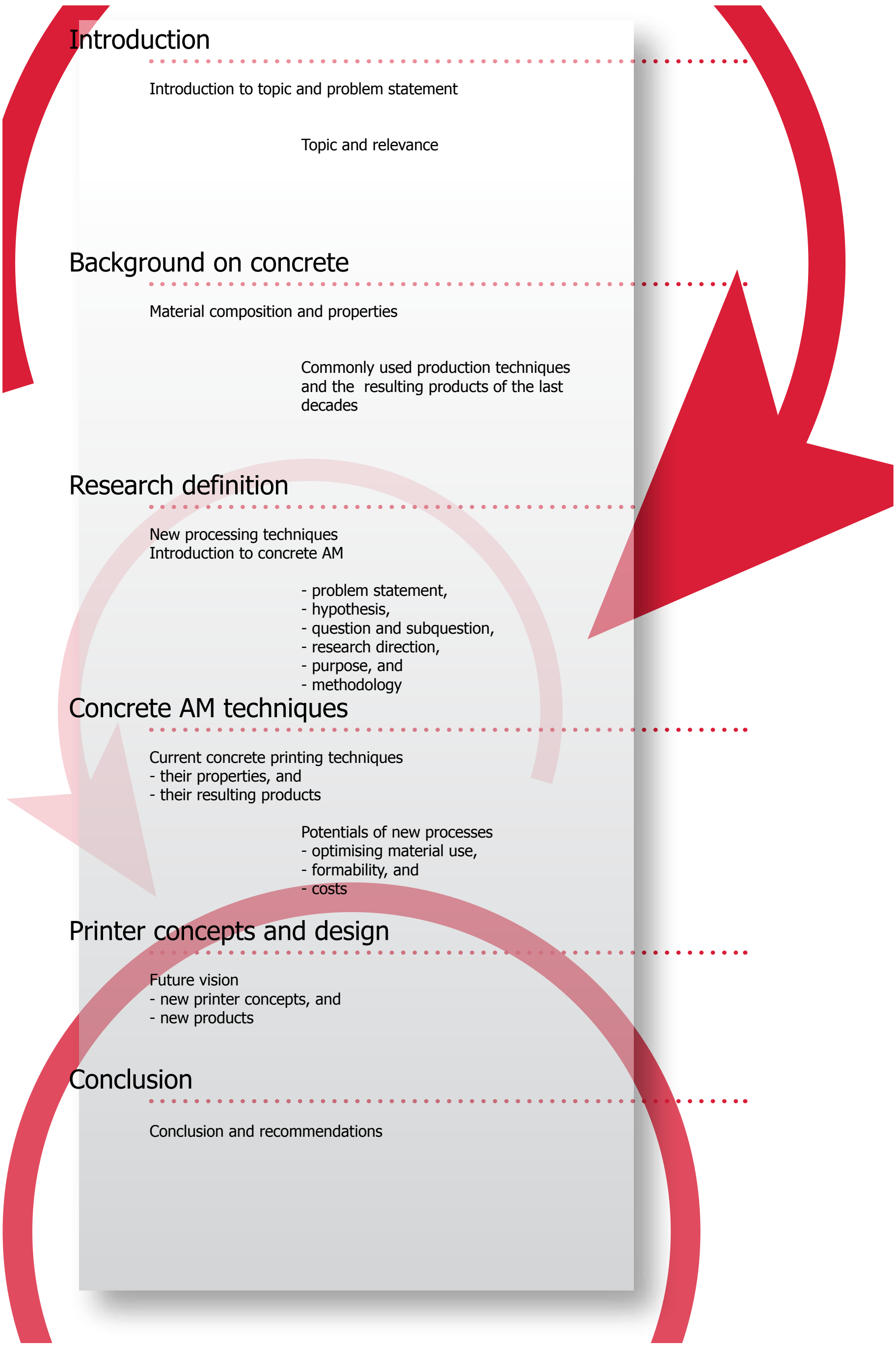


Figure 1 - Schematic structure of thesis

Abstract

This thesis examines the additive manufacturing (AM) of concrete, its possibilities, feasibility and advantages over existing techniques. The first part generally focuses on the characteristic properties of concrete that are important and how they relate to an AM method, for instance aggregates and reinforcement. After this extensive introduction in the field of concrete and AM, the current situation regarding additive manufacturing of concrete is described. On the basis of literature resulting products are shown and discussed. Their characteristics are compared to detect a match or mismatch between the AM technique and the produced elements. The outcome of this evaluation is used to describe improvements which are elaborated in the second part. This design part consists of a roadmap that shows a future vision. Concrete is a new material in the field of additive manufacturing. Since it is one of the materials that hardens by a chemical reaction, considerable attention needs to be paid to the workability of it in an AM process. Traditional processing techniques are adapted to these characteristics but concrete does not let itself dictate how to behave. The roadmap envisions how the technique has to evolve in order to implement the characteristic properties of concrete. The possibilities for products made with an additive process are endless, but just replacing existing production methods with additive ones is impossible. Although improved freeform production techniques are still the aim of this research, this does not mean that more freedom in form is by definition the largest improvement that AM can offer at the moment. From another point of view the implementation of additional functions in traditional products can be of great value.

Product ideas and an evaluation of the techniques shown in the vision are related to the developments to achieve an increase in speed, surface quality and strength in the AM production technique, next to the requirements that have to be set regarding a matching fresh concrete mixture. These essential aspects of the process lead to the important conclusion that in the AM of concrete, both material and production technique have to be matched precisely. Next to matching process and material it is important to match process and product. Concrete is widely used and not all products should be made using an AM process. Simply copying standardized elements does not add the added value layered fabrication methods can achieve if used adequately.

Contents

I Literature review

1 AM of concrete

There is a considerable amount of labour and material involved in building a concrete structure. Moulds need to be made, reinforcement placed, concrete casted and afterwards the mould has to be removed. This process has been optimised constantly to decrease costs and improve performance. Due to the optimised processes, an abundance of elements are standardised, since these standardised elements can be produced in large series, which helps in recovering the investments. Structural optimisation is in this production chain inferior to the related costs and profits. This approach results in repeated and over dimensioned elements. The lack of freedom in shape is another limitation. Due to the standardised elements the designed freeform façades are divided in sections, which is done in such a way that the façade can be build from standardised elements.

In addition to these disadvantages, the rationalisation of the construction process resulted into very efficient spanning elements with reinforcement as well. The reinforcement is used, instead or in combination with shapes that are geometrical optimised, to cope with the applied stresses. In addition to the primarily function of minimising tension in the concrete, the reinforcement is used to achieve a kind of structural variations. By adjusting the amount and location of the reinforcement, the structural capacity can be changed, so long as it fits between the limits of the production process.

This chapter explores these challenges of concrete in more detail.

§ 1.1 *Concrete formwork*

Construction companies face several important challenges concerning the costs of production. Firstly in situ concrete casting process produces a lot of waste material that is thrown away afterwards. Especially if not reusable formwork is used (Tam, Tam, Chan & Ng, 2006, p.1), while in contrast reusable moulds decrease this flow of waste. Since reusable moulds are rather expensive large series are needed to make these moulds cost effective, which in turn causes a lot of repetition, for example in façade elements.

The construction industry has not only to deal with not reusable moulds, but also with over constructed elements due to limitations in the production processes. Costs are strongly correlated to production techniques. Hence a lot of elements are standardised, to decrease costs even more. Adjusting a standardised element to reduce the material use, will not be cost effective, since the dead load in buildings is not that important as in airplanes. It does not affect the energy use in its service life significantly and sometimes it is even favourable to have more mass in a building to temper the fluctuations in temperature (Peck, 2013, p.36).

A lot of freeform elements are casted in situ, although quality of in situ concrete is harder to control (Elhag et al., 2008, pp.376-377). Therefore, high performance elements are made in controlled environments. Due to limitations in the size of the products that have to be transported afterwards, these elements are generally a part of a standardised building system.

Concerning the Life Cycle Assessment (LCA) of in situ concrete it can be concluded that this assessment is negatively influenced by in situ casting. Especially over ordering of concrete (Tam, et al., p.9) and wearing of formwork (Cole, 1998, p.340) are the main contributors to added CO^2 emissions of in situ concrete casting. Since hardening of concrete produces CO^2, it is desirable to have a look at the LCA so that the evolved production process has not only an economical but a sustainable motive as well.

Figure 2 - Zilverparkkade concrete façade by René van Zuuk Architekten [1]

[1] Rozemeyer, 2013

§ 1.2 *Freeform concrete in architecture*

The use of digital modelling increases in architecture, but to make such freeform shapes is very hard, since it is either impossible or extremely costly. There are currently no industrial concrete production techniques that can cope economically with both these criteria.

Moulds can be made out of different materials, like steel, wood or plastic, and by different methods like; carpentry, CNC milling of wood, steel or plastic and by "printing" materials (AM).

Some freeform moulds are made out of CNC milled plastic or plastic that is inflatable. This is still a relatively expensive way of constructing and will only be feasible if there are sufficient projects using the same mould. If processing concrete without moulds becomes possible, more 3D designed structures can actually be built the way they were designed. In a time period in which everything is designed digitally, the manner of designing and building is not synchronised anymore, which is shown by the fact that it is possible to design such material optimised structures that either cannot be build, or are absolutely not cost effective. In general, the use of automated robotic construction methods, as already present in automotive industry, are not used in the construction industry (Buswell, Soar, Gibb, & Thorpe, 2007, p.224).

§ 1.3 *Topic and relevance of the research*

Moulds and formwork are the limiting factor in today's concrete processing, either due to process limitations or due to costs. The relevance of AM increases because of the fact that architects and engineers design constructions in the 3D environment. Unfortunately, the benefits of this way of designing have to deal with the limitations during construction. As mentioned previously, there is no production technique that can easily handle elements with different properties in a cost effective way. This can be changed if elements or formwork can be manufactured with a production process that builds elements by adding layers on top of each other, i.e. Additive Manufacturing (AM).

Imagine how the Zilverparkkade's façade pattern (figure 2) would look like if repetition was unnecessary. The form of the branches could be different all over the façade. They could differ in thickness in direct relationship to the forces applied to the façade cladding. Maybe there would be voids inside the elements to decrease the material used and to increase the moment of inertia. Almost everything is possible using an AM technique.

This thesis will evaluate existing concrete AM processes and show potentials of new ones in order to minimise the gap between the designing and production of freeform concrete elements.

2 Background on concrete

Concrete has been widely used by the ancient Romans during a 700 year time span. The Colosseum and the Pantheon, which has different concrete compositions (figure 3), are prime examples of that usage. Before the Romans, the Greek used lime and pebbles to make concrete floors in the royal palace of Tiryns in 1400-1200BC. Other impressive, more recent, concrete structures are the Hoover Dam, the Panama Canal and the 828 meter tall Burj Khalifa. All these structures share the construction method that uses some kind of formwork.

Concrete itself is a composite material that consists of granulate and cement that reacts during curing to become cement stone which binds the composite together. The consumption of concrete is around 25 billion tonnes annually and it is by far the most used building material (figure 4) (Ashby, Shercliff & Cebon, 2007, p.481). The worldwide consumption of cement was 3004.7 million tonnes in 2009 (Peck, 2013, p.13).

Additive Manufacturing (AM) techniques can become dominant, as the construction industry starts to shows interest in its potentials, but first useful knowledge of concrete has to be gathered.

§ 2.1 *Concrete - the material*

The words cement and concrete are sometimes interchanged. To clarify the distinction; cement is the binding material in the concrete that holds the aggregates in position. Cement is the most costly element in concrete. That is why around 80% of the volume of concrete consists of some kind of granulate. A generally known ratio of materials used is, one part cement, two parts sand, three parts gravel and water. In the Netherlands, blast furnace cement is the most used type of cement. The aggregates have different sizes, where the smaller particles fill the voids between the bigger ones. Near the surface, in the concrete's skin, there are relatively more fine aggregates (figure 5). The cement needs to cover all the surface area of the aggregates to bind all the materials in the composite. The bounding between the cement and aggregates is completed by the use of water. Too little water causes incomplete bounding (figure 6), too much will result in porous concrete (Callister, 2007, pp.582-583). The ratio between the amount water and cement is called Water Cement Ratio (WCR). To cover more smaller aggregates, extra cement and fine materials are needed. Cement because the surface/volume ratio increases, fine

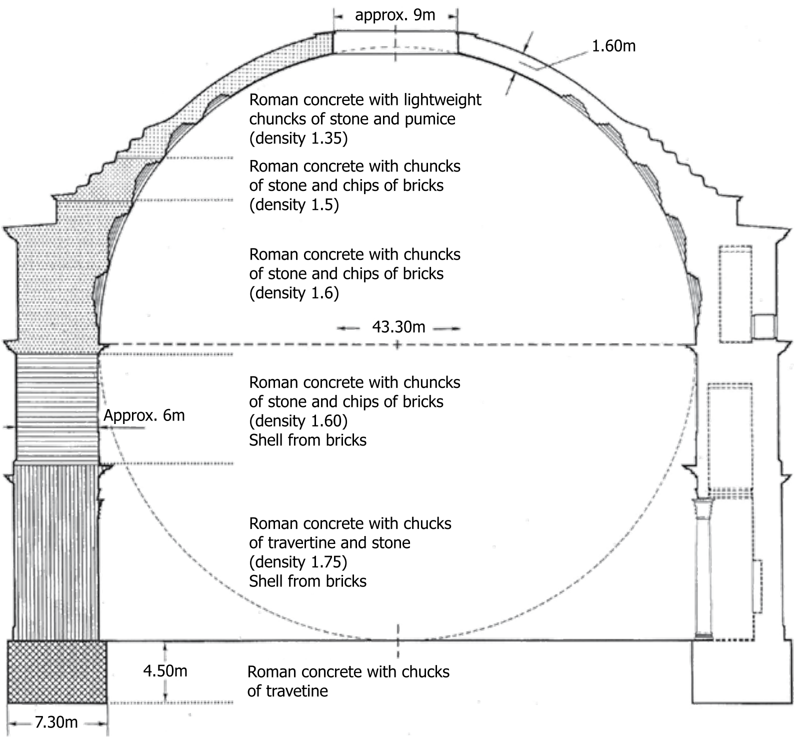


Figure 3 - Pantheon its different layers of concrete (1)

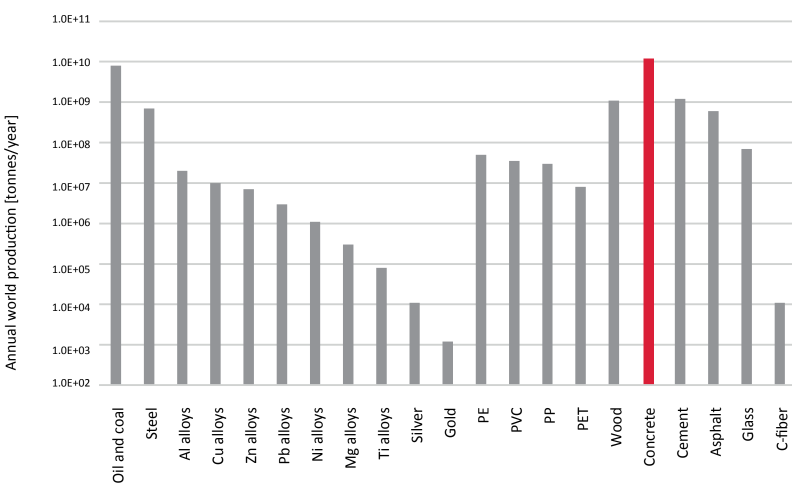


Figure 4 - Consumption of hydrocarbons and engineering materials (2)

[1] Lambrecht, 1993 in Peck, 2013, p.10
[2] Adapted from Ashby, et al, 2007, p.481

material because the gravel has less voids in comparison to fine sand. In 1 m^3 fine sand is 43% empty space in comparison to only 36% in 1m^3 gravel (table 1) (Berg, Buist, Souwerbren & de Vree, 1995, p.56). The latter can also be found in the density of the two materials, 1500 kg/m^3 versus 1700 kg/m^3, that have both their origin in a rocky material with a density of 2650 kg/m^3. Section 2.1.3 contains more information about the deposition within the concrete.

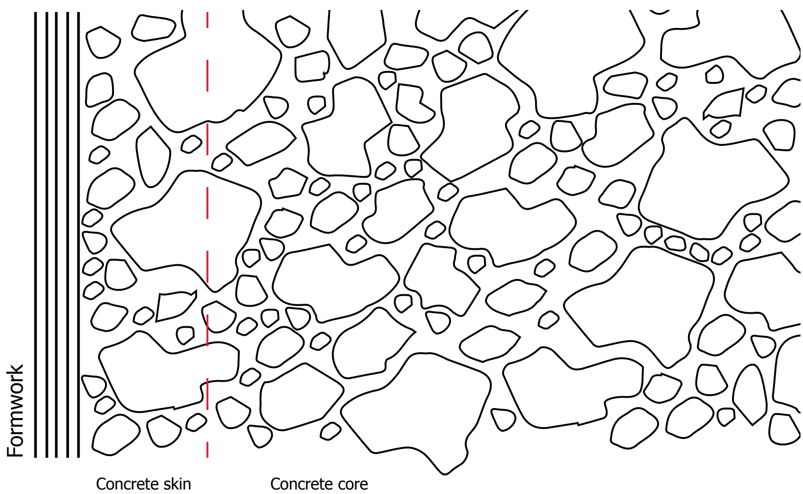


Figure 5 - Distribution of aggregates in the core and near the formwork (1)

Aggregate	Grain size	Modulus of fineness	Surface/volume (m2/m3 = m1)
Sand dust	0-0.05	0.5-0.8	135000
Fine sand	0.-0.2	1-1.5	26500
Coarse sand	1-3	2-3	2400
Fine gravel	7-12	4.5-5.5	560
Gravel	12-25	6-7	220

Table 1 - Aggregates surface/volume ratio (2)

1 Adapted from Berg, et al., 1995, p.55
2 Berg, et al, 1995, p.67

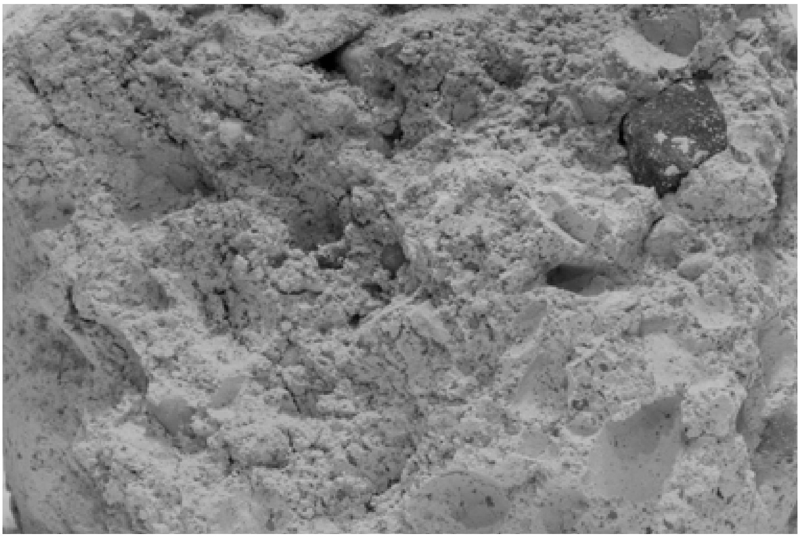


Figure 6 - Porous concrete

Probably one of the most important features of concrete is its price. When compared to other materials, its Young's modulus compared to density falls in the expected range. If the production costs for materials relative to those of steel are compared to their Young moduli, a shift can been seen for concrete. It has the highest Young modulus of all materials in that price range (figure 7 and 8).

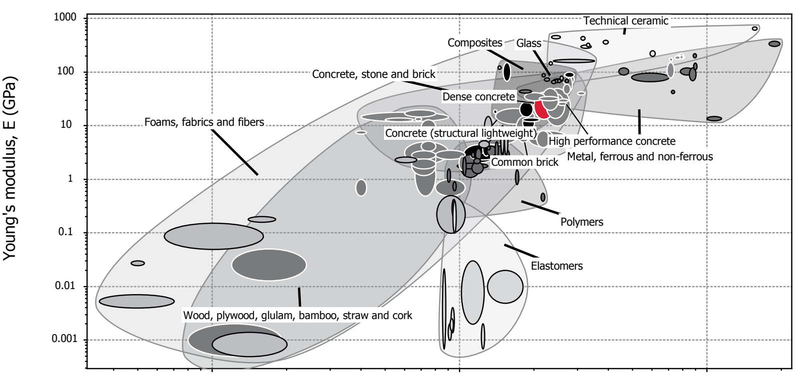


Figure 7 - Young modulus-Density (CES)

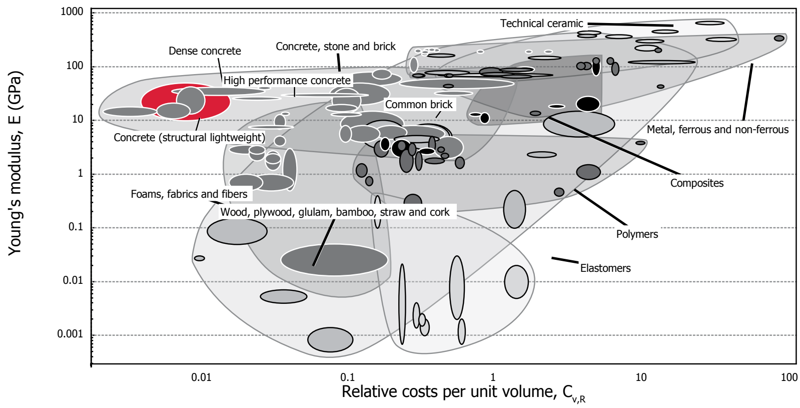


Figure 8 - Young modulus-Relative cost (CES)

§ 2.1.1 *Terminology*

Remarkable is that only a cementitious material is called concrete when the composite contains aggregates that are both, smaller and bigger than 4 mm in diameter. In the properties of concrete mixtures, plasticity, workability and consistency play a major role. Important properties of concrete are especially the strength and durability. Strength is obtained by the kind of mixture, aggregates and reinforcement used. The combination of these variables in combination with the point of time in the hardening process determines the strength of the concrete. The strength at a certain point in time can be very important if an element needs to be de-moulded and transported. If an element can be de-moulded and transported directly after production this is called green strength. The fresh concrete used for this is most of the time a fresh concrete with very little water, called earth dry.

Durability has to do with the resistance against the elements, frost, high temperatures, the reaction with sulphates, acids, seawater and erosion. All these properties can be regulated with the type of mixture (Berg, et al., 1995, pp.11-19).

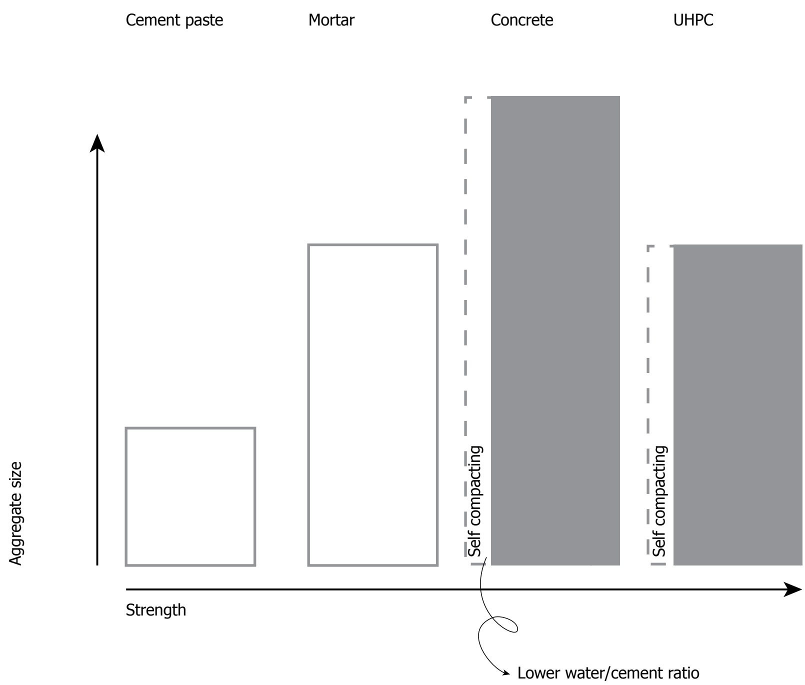


Figure 9 - Concrete labelling

§ 2.1.2 *Cement types*

Three commonly different cement types used are:

- Portland cement,
- Blast furnace cement, and
- Portland fly ash cement.

The difference between these lies in the chemical bounding that occurs during hardening. The pore structure of 65%+ scoria blast furnace cement is more closed. This results in concrete that is extra chemically resistant. The hydration speed of blast furniture cement is higher as well. It decreases the curing time at higher temperatures. On the other hand this results in an increased curing time at lower temperatures. To prevent the blast furnace concrete from drying out, extra treatment after casting is needed, in contrast to Portland cement. Another characteristic of blast furniture cement is that it emerges less warmth during the curing, making a thick construction less vulnerable for cracks. Both have their advantage and disadvantage properties that need to be considered when choosing a mixture. Besides the type of cement the type of fresh concrete differs. There are cement pastes and mortars, but concrete itself can be divided in concrete and Ultra High Performance Concrete (UHPC). The latter does not fulfil the requirements to call it concrete, but that is due to the old standards. Nowadays they are accepted as concrete since their overall characteristics are in line with concrete as formulated in literature. In addition to this division, there is also a difference between self compacting and not self compacting concrete. The compacting behaviour has to do with the WCR and additives like plasticizers. Generally it can be said that the WCR increases for self compacting mixtures and that because of that they are considered weaker (figure 9)

Material	Density (kg / m^3)
Portland cement	3150
Portland fly ash cement	2900
Blast furnace cement	2950
Fly ash	2000 - 2200
Rockdust	2650
Trass	2300
Sand and gravel	2650
Sand and gravel (from the ocean)	2650
Basalt	2750 - 3150
Limestone	2200 - 2750
Quartzite	2600 - 2650
Granite	2580 - 2850
Porphyry	2710
Magnetite	3500 - 5100
Baryte	3400 - 4300
Steel	7650
Lytag 4-8 and 4-12 mm	1850
Concrete granulate	2250 - 2450
Masonry granulate	1300 - 1950

Table 2 - Concrete materials with their densities (1)

1 Berg, et al., 1995, p.178

§ 2.1.3 *Disposition within the composite*

The aggregates contribute considerably in the final volumetric mass of concrete and they need to be chosen in such a way that they fill the voids between each other. The remaining voids are filled with the cement which holds the aggregates together (see table 2 for the ingredients of concrete with their density and table 3 and figure 10 for an example of a distribution of the sizes). This does not necessarily mean that mixtures with a high fragment of cement are weaker. The cement stone formed out of

Sieve NEN 2560	1st specimen	2nd specimen	average	%	cumulative	rounded
C31.5	0	0	0	0	0	0
16	115	119	117	11.7	11.7	12
8	282	282	282	28.2	39.9	40
4	253	247	250	25	64.9	65
2 mm	56	45	50.5	5.0	69.9	70
1 mm	74	63	68.5	6.8	76.7	77
500 µm	89	110	99.5	10	86.7	87
250 µm	69	71	70	7	93.7	94
125 µm	48	52	50	5	98.7	99
remainder	14	11	12.5	1.3	-	-
total	1000	1000	1000	100	-	Fz=5.44

Table 3 - Example of grain distribution

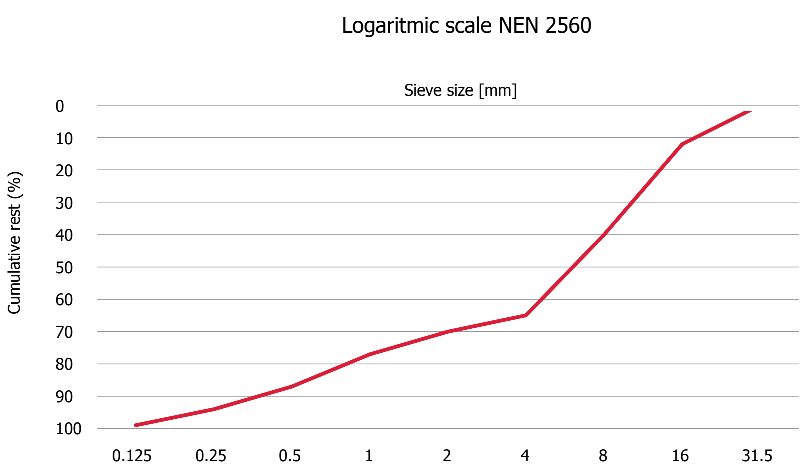


Figure 10 - Example of grain distribution

the cement can be considered as very strong. Fracture occurs mostly at the bounding surface of the aggregates and cement stone. Even in a mixture with a lot of cement like UHPC, the strength relies on both the cement stone and aggregates. Figure 11 shows respectively a mixture that has a bad composition, a good disposition and one of an UHPC.

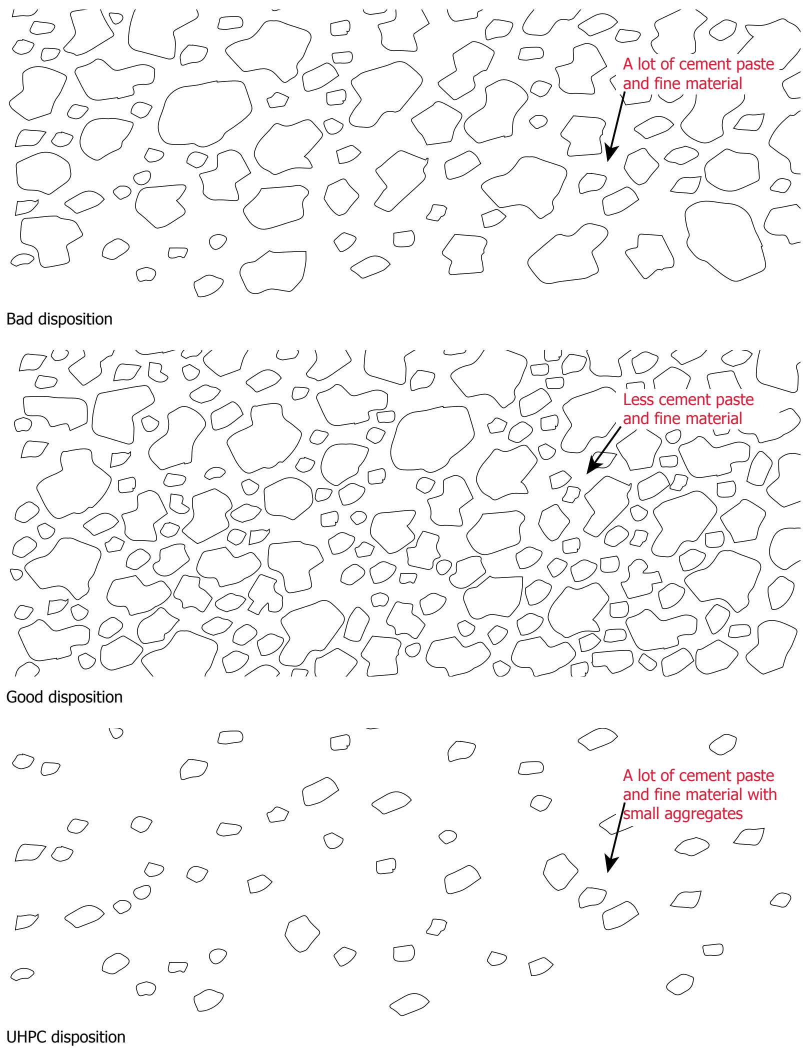


Figure 11 - Aggregate disposition

The concrete behaviour during curing is influenced by the reaction type itself and the relation to the deposition of the material.
The deposition of the materials in the concrete determines the product characteristics. The ratio of large aggregates, small aggregates, sand and ash within the mixture determines the amount of cement and water needed, since the cement and water need to 'glue' the concrete together. Aggregates that are porous will absorb some water which has to be taken care of by adding an additional amount of water in the fresh concrete mixture. After the mixture is calculated, during processing, the compacting of the mixture is important to obtain the desired strength. Every percent of air that stays inside above the 1-2 percent will decrease the final strength by 5 percent (Berg, et al., 1995, p.113). If the mixture decomposes the aggregates are not distributed equally anymore, influencing the concrete's characteristics in a negative way. The different materials within the fresh concrete mixture start to float on top of each other. A mixture with very light aggregates is more vulnerable than a mixture that contains relatively heavy aggregates. Wet mixtures with a high WCR are also vulnerable, because the light water will be segregated by too much compacting. It is highly important to compact the concrete without decomposing the mixture.
The cement paste is in addition to the distribution within the fresh concrete mixture very important. The cement and water forms cement paste. During curing this hardens and the space between the formed cement stone is filled with hydrates. Too much water to process the concrete easily leads to more, so called capillary pores, in the concrete. These pores are visible by eye. There is simply too much water for

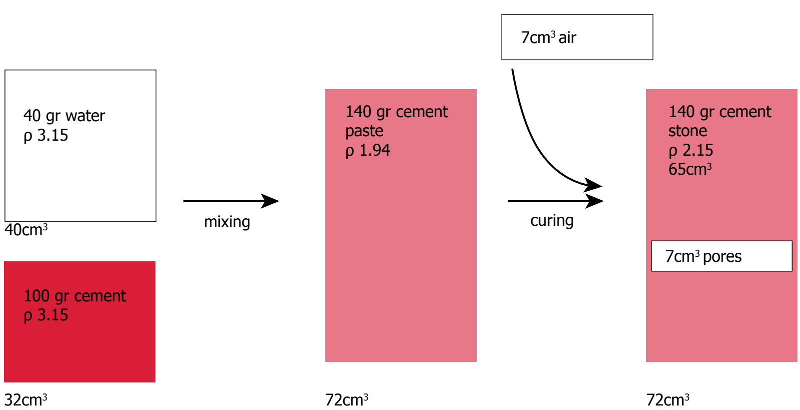


Figure 12 - Curing of Portland cement

the reaction and gel pores. There will always be some pores in the concrete stone because the chemical reaction binds the water chemically within the cement paste. 100 gram of Portland cement will use 25 gram of water to completely hydrate and an additional 15 gram will be kept in the gel pores. Theoretically 100 percent hydration needs 40 gram of water, the WCR should not be lower than 0.4. Internal shrinkage causes that when 100 gram cement is hardened 7 ml air or water is absorbed (figure 12). This happens because the volume of the element does not decrease (concrete internal shrinkage), but the reaction creates material that has a higher density. Since there are no vacuums in the concrete, voids appear. Comparable to the cracking of clay (figure 13). If the WCR is lower the concrete will, if it is hardened under water, use some water to hydrate the unhydrated cement.

With a higher WCR the reaction time decreases and the amount of capillary pores will increase (figure 14). For example if the WCR is 0.33 the relative strength is 1. When the WCR increases to 0.55 the relative strength will decrease to 0.42 (table 4) (Berg, et al. 1995, p.135).

During hardening different reactions take place and 100% hydration is hard to reach, even with higher WCR's. Figure 15 shows the internal distribution during hydration. This explains why the relative strength of a mixture with a WCR of 0.33 instead of 0.40 is equated to 1.0.

The fresh concrete consists of the cement, aggregates and water. Since the aggregates will not shrink or take part in the reaction, the internal shrinkage and pores only affects the cement paste in between of them. Since the cement paste acts as the glue within the concrete mixture it has to cover all the aggregate material. If

Water cement ratio	Relative strength
0.33	1.00
0.35	0.91
0.40	0.74
0.45	0.60
0.50	0.50
0.55	0.42
0.60	0.35
0.65	0.30
0.70	0.26

Table 4 - WCR and relative strength [(1)]

[1] Berg, et al, 1995, p.135

the aggregates material is stacked very compact to each other, the internal shrinkage will be minimised. With a very high cement to aggregate ratio the internal shrinkage will increase, but not necessarily lead to a weaker concrete. The standard aggregates are in high strength concrete not strong enough anymore and often their surface is too smooth for a good binding. For this reason granite stone is used to increase the performance of in this case the weakest link, the aggregates, in high strength concrete.

Figure 13 - Cracking of clay

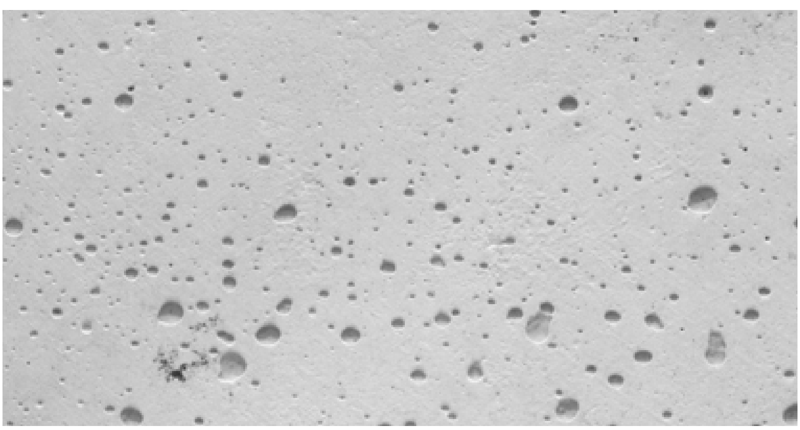
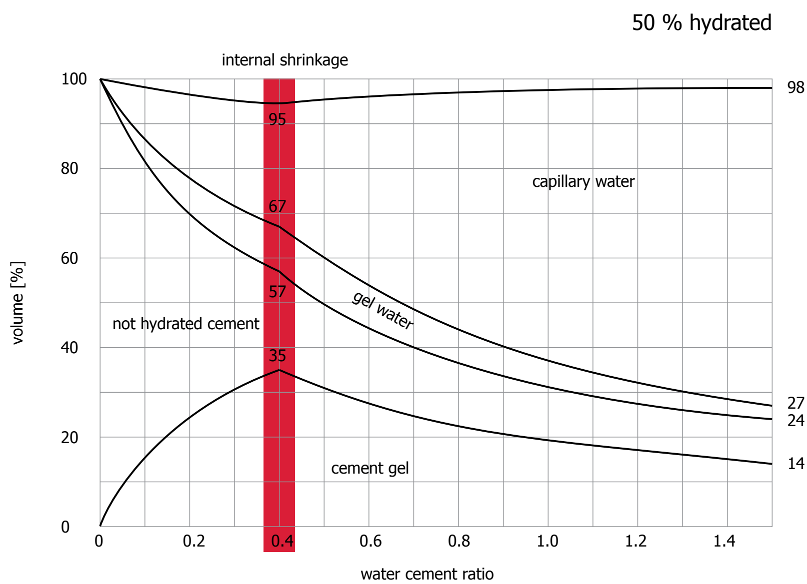


Figure 14 - Cement capilary pores



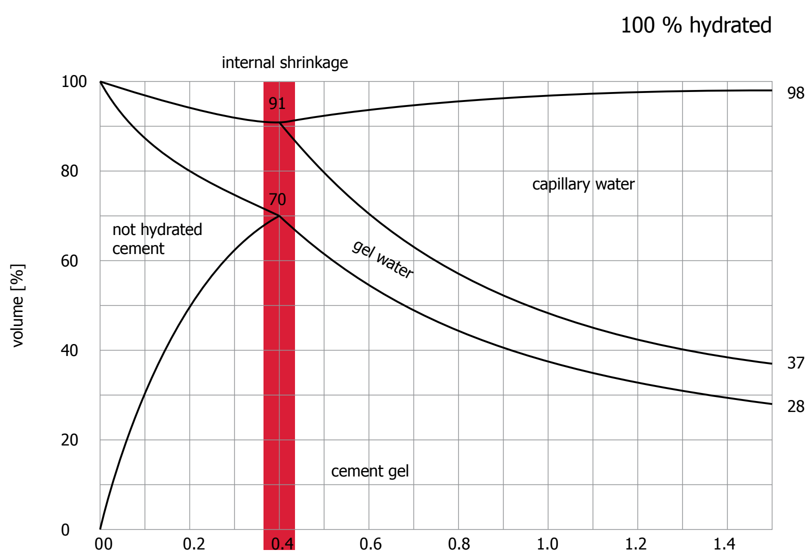


Figure 15 - 50% and 100% hydration of cement [(1)]

[1] *Adapted from Berg, et al., 1995, p.134*

§ 2.2 *Concrete processing techniques*

A variety of concrete processing techniques have been developed the last decades. Pierre Luigi (1891-1979) experimented with ferrocement and structural prefabrication during his career (Iori, 2009, pp.23-27). After the second world war, the shortage of housing triggered the construction industry to rationalise. New standardised systemized products followed by tunnel formwork, were used to build multistory residential buildings out of blocks and beams. Tunnel formwork is a rationalised on side concrete casting process that is used to make walls and floors of a building at once (figure 16). Comparable to tunnel formwork is climbing formwork. Instead of making horizontal compartments it is used to make (stability) cores for high rise construction (§3.3).
Table 5 shows a comparison of in situ and prefabricated concrete.

	In situ	**Prefabricated**
Material waste	yes	none (failed elements will be recycled)
Transport	Raw materials	Elements
CO2 emission	Depends on condition	As low as possible
Quality	Depends on condition	As specified
Planning	Costs time at the construction site	Are fabricated before application
Equipment at the construction site	- Moulds - Preparation of reinforcement - Concrete processing equipment like concrete pump and poker vibrator - Extra construction workers	- Crane - Mounting hardware
Material use	Over constructed due uncertainties in quality	Optimised
Embodied energy	Differs	Differs
Form	Limited by mould	Standardised

Table 5 - In situ and prefabricated concrete processing properties

Related to the different processes, the mixtures have been adapted as well. Concrete with strengths up to C80/95 are not that uncommon anymore in an era where UHPC reaches strengths over 150MPa.
C80/95 high strength concrete can, like Ultra High Performance Fibre Reinforced (UHPFRC) that is reinforced with fibres, cope with greater compression loads, but in

Figure 16 - Tunnel formwork

case of increased tension loads extra reinforcement is needed. As showed in figure 9 of both concrete types there is a self compacting mixture which has been adapted to the newer production processes and allows the fresh concrete to compact itself between the increased amount and density of reinforcement bars in the formwork.

Formwork

Formwork is used for casting concrete. There are two categories of formwork;

- Standardized formwork (tunnel formwork, climbing formwork), and
- Customized formwork (in situ formwork).

The standardized formwork systems are made out of steel. It is reusable strong and gives a high quality surface finish. The customized formwork can be made using different techniques;

- Carpentry,
- By the use of polystyrene sheets,
- Additive Manufacturing (e.g. 3D-printing), and
- Subtractive manufacturing (Milling).

Extrusion

Automated processes use a die and no formwork to extrude the concrete. Hollow core slab floor elements are made this way. The extrusion techniques rely on the green strength of the concrete.

§ 2.2.1 *Processing and the environment*

For the durability of concrete it is very important to select the right mixture. If the environmental impact of concrete is examined, generally it can be remarked that in situ concrete produces more CO^2 than prefabricated concrete elements. This is caused by the fact that the climate during in situ concrete casting can not be regulated (Elhag et al., 2008, pp. 376-377). The standardized concrete elements are generally speaking over dimensioned. To lower the LCA of concrete used in the building industry, new mixtures have to be composed, or the production processes have to optimised in order to optimise the material usage. The transport should also be taken into account, however the transport sector is changing. It can be expected that in addition to electric cars, electric or hydro lorries will be used in the future. It depends on the source of the energy whether it is environmental friendly or not. Until then, CO^2 production embedded in the transport should be taken into account. Also, if concrete is casted in situ, a lorry is needed to deliver the fresh concrete.

§ 2.3 ***Conclusions concrete***

Although concrete is a material that is widely used, the chemical reactions and the cement hydrates that are formed are very important for the characteristics. During the last few decades the knowledge about the chemical reaction has increased. Nevertheless the processing techniques have hardly evolved if compared to the quality of the mixtures. However the construction industry is also well known for its conservative behaviour regarding new techniques, which could suggest that evolving beyond standardized elements is not economically beneficial, or that the best way of processing is still by using formwork. Nevertheless the expertise on concrete mixtures of the last decades will be very valuable when introducing new processing techniques like AM.

3 Additive Manufacturing

What is Additive Manufacturing (AM) and why would the building industry need this process? This chapter introduces the AM technique. AM is a production method that uses a process of adding layers on top of each other, to build a component. AM processes also exist in nature. Stalagmites are an example of uncontrolled AM columns.

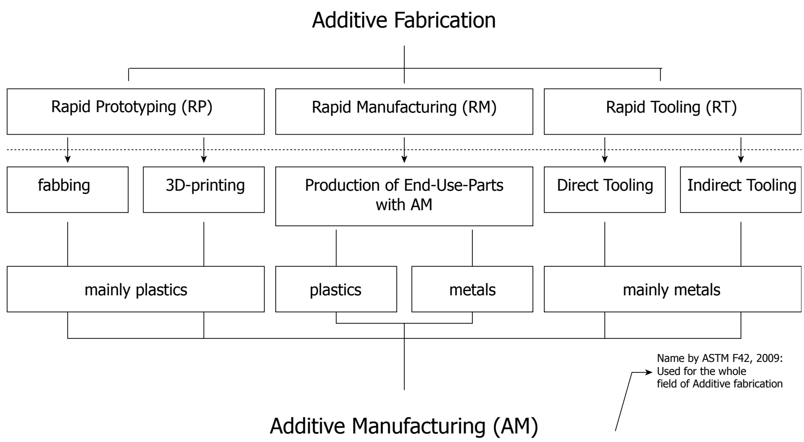


Figure 17 - The term additive manufacturing [1]

§ 3.1 *Introduction to AM*

AM is marketed as a production method that can solve all production problems that are encountered nowadays. It is like the promotion of every new technique. AM has potential, but is a relative new technique that requires some improvements before it reaches the desired potential. It has been improved in the last three decades, but it took some time before it was picked up by the construction industry (Knaack, Klein, Bilow, & Auer, 2007, p.126)

AM has been adopted as a general term for multiple fabrication techniques like, rapid prototyping, layered fabrication, rapid manufacturing, freeform fabrication, additive fabrication, layered manufacturing, direct digital manufacturing, additive manufacturing (figure 17) (ASTM, 2009 in Strauβ, 2012, pp.18-19). In this thesis the terminology AM will be used for multiple fabrication techniques as well.

The AM process can easily be automated, reducing labour costs and additional work

[1] *Adapted from Strauβ, (2012) p.19*

Family tree AM techniques

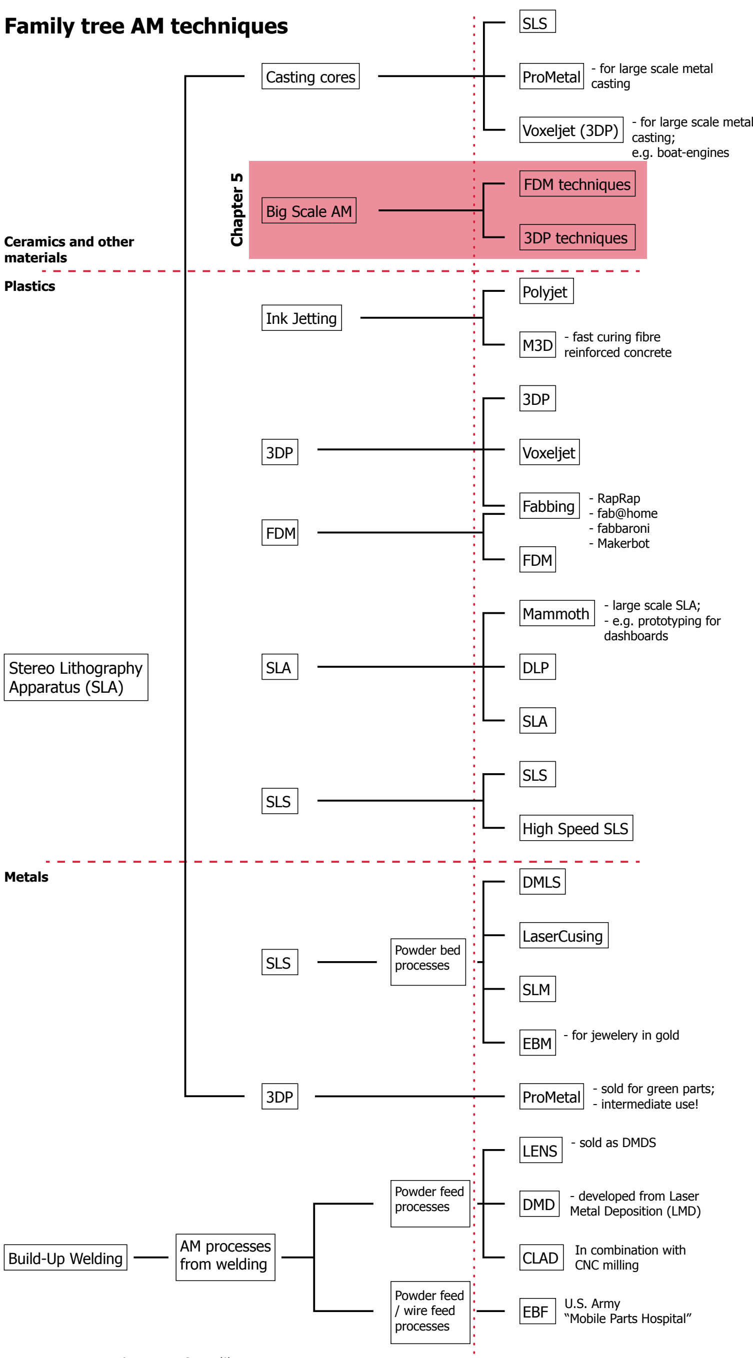


Figure 18 - Family Tree of AM [1]

[1] *adapted form Strauß, 2012, p. 37*

afterwards. Additional work includes removing material but also the handling of the raw materials itself (Pegna, 1997, pp.429-430).
The construction industry is very conservative. They rely on standardised elements, even though there is a desire that all buildings should look different. The industry is innovating, but AM is still not employed on a large scale. In other industries, like the automobile industry, AM starts to play a significant role.

§ 3.2 ***AM methods***

There are different AM techniques. The scheme (figure 18) from Strauβ (2012) shows the different categories in the field of AM, based on the type of material. The most relevant techniques to understand the concept of AM are available for plastics. These are explained in this chapter and followed by general information about the characteristics. In this section the information is based on AM Envelope - The potential of Additive Manufacturing for façade construction by Holger Strauβ, that contains specific and in depth information on AM.
AM techniques can also be divided in two trends;

- Fusing materials, and
- Gluing materials.

The first mechanism uses only the material applied during an AM process, while the second mechanism uses two types of material to build the element.

§ 3.2.1 *Stereolithography*

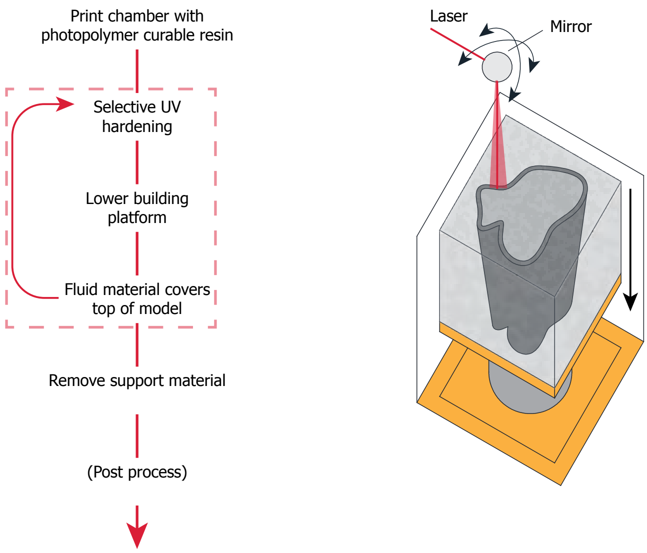


Figure 19 - SLA method

Stereolithography (SLA) uses an UV light source to cure parts of the light sensitive resin. The light traces the model in the computer. After one layer is cured by the light the building platform is lowered and new material is cured on top. Support material is still needed and has to be removed afterwards. The thickness of the layers can be reduced to 0.05mm.

Material	Photopolymer curable resin
Resolution	0.05mm
Curing mechanism	Hardening by UV from laser
Moving parts	Focus mirror, print table

Table 6 - Characteristics stereolithography

§ 3.2.2 *Laser Sintering*

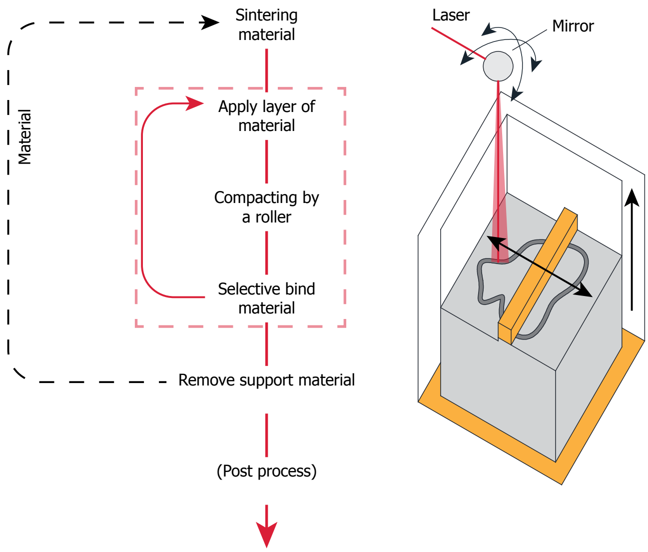


Figure 20 - LS method

Laser Sintering (LS) is a method that uses powder instead of a liquid. The powder is put on top of the existing layer while the platform is lowered. A light source is still used to selective melt and fuse the material. The melted material forms the final element. Because the powder is more stable than a liquid, no support material is needed.

Material	Plastic, ceramic, metal and glass
Resolution	0.1mm
Curing mechanism	Sintering by laser
Moving parts	Focus mirror, material distributor and roller

Table 7 - Characteristics stereolithography

§ 3.2.3 *Fused Deposition Modelling* (1)

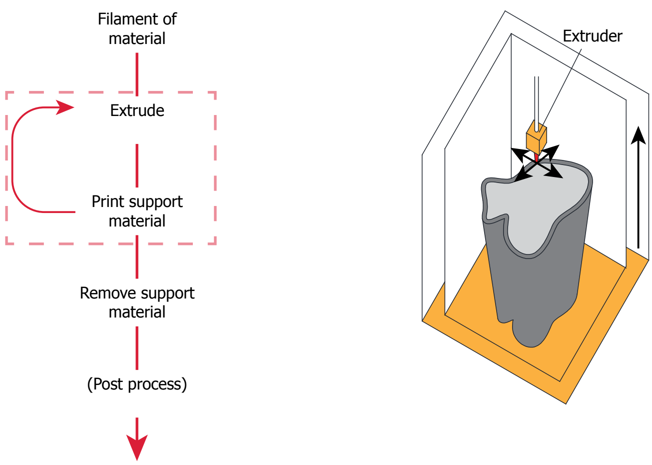


Figure 21 - FDM method

Fused Deposition Modelling (FDM) uses a filament that is heated and extruded by a nozzle. The extruded molten material sticks directly to the layer underneath. Support material is needed for overhangs and not well stabilised components. This support material has to be removed afterwards. The layer thickness is between 0.127 and 0.330mm.

Material	Plastics, rubber
Resolution	0.127
Curing mechanism	Fusing filament
Moving parts	Extruder head

Table 8 - Characteristics stereolithography

§ 3.2.4 *3D-Printing*

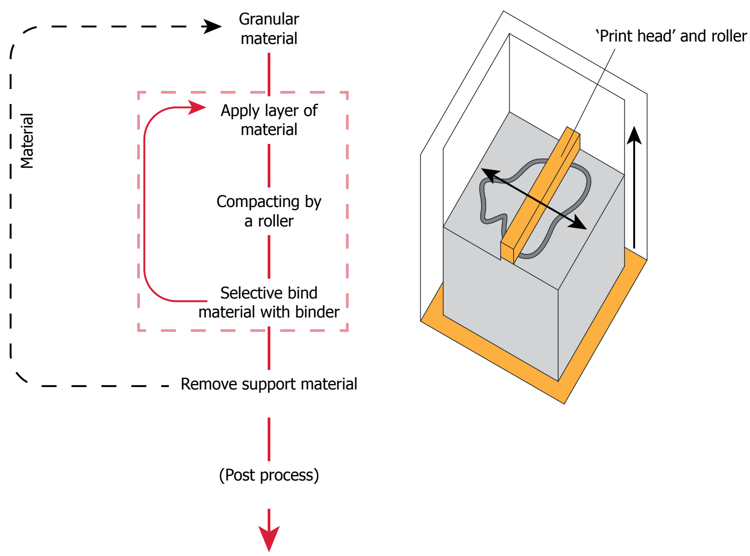


Figure 22 - 3DP method

3D-Printing (3DP) looks like LS, but instead of light, a binder is used to bind the powder. It is like a printer that puts ink on a sheet of paper. Like LS, after printing one layer, the platform is lowered and a new layer of powder is applied on top of the model. Support material is not needed and the layer thickness varies between 0.09 and 0.10mm

Material	Gypsum
Resolution	0.09
Curing mechanism	Liquid binder
Moving parts	Printhead and roller

Table 9 - Characteristics stereolithography

§ 3.2.5 *Polyjet*

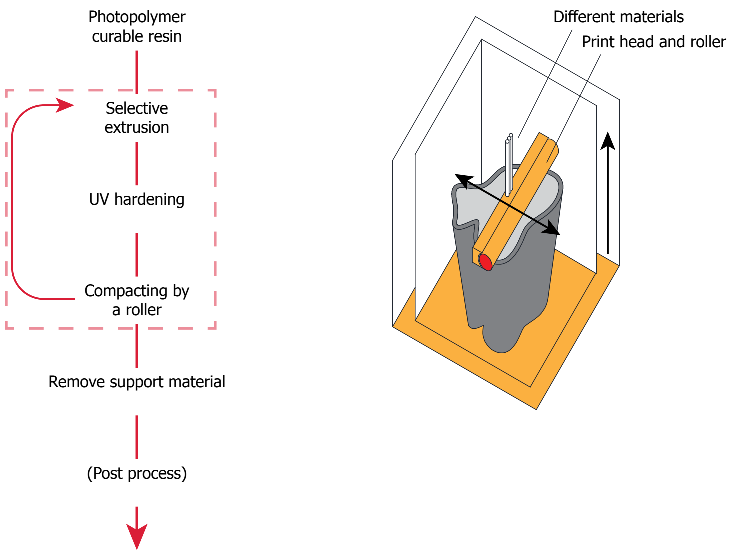


Figure 23 - Polyjet printing

Polyjet printing uses multiple nozzles with a highly liquid material to build / extrude the element. Those nozzles are fitted in the printhead that moves over the platform. In this printhead a light and a roller are embedded to cure and smooth the applied layer of material. The layer thickness is between 0.016 and 0.030mm. Because of its high resolution, a very smooth element is guaranteed. Support material is needed like in other methods, that build / extrude only the material that is needed.
The nozzles allow to print with different materials at the same time. Gradient material is not possible yet, but there are already experiments going on with so called true seamless gradient materials.

Material	Photopolymer
Resolution	0.016
Curing mechanism	Hardening by UV from laser
Moving parts	Printhead with integrated roller and laser

Table 10 - Characteristics stereolithography

§ 3.2.6 *Other AM techniques*

The AM processes described before are based on a printing mechanism that use a chamber to build in. The extruders move in or at the sides of the chamber. Robotic arms is a new trend in AM. If desired they can be mounted on a rail system to operate on a larger work platform. Instead of the fixed position extruders on a rail, these arms have more degrees of freedom. If an extruder head can move in 6 directions instead of 3, other processing techniques can be used. The printers in a chamber use only the three translation degrees of freedom;

- Along the x-axis
- Along the y-axis
- Along the z-axis

The additional three degrees of freedom come from rotation;

- Rotation around the x-axis
- Rotation around the y-axis
- Rotation around the z-azis

These three are available for the robotic arms and Joris Laarman shows such an arm from ABB that prints in the open air. The project operates under the name MX3D. At the moment two types of material are processed with MX3D, steel and a polymer. The steel is a welding machine that builds by welding layers of steel on top of each other (figure 24) and the polymer can be compared to a two component adhesive. Before extrusion it is mixed in just before the nozzle and after extrusion it reacts very rapidly,

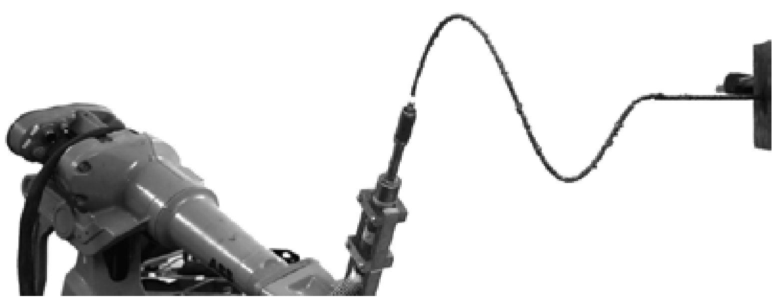


Figure 24 - MX3D Metal [1]

[1] MX3D, 2014

especially because additional heat is added by use of a hot air gun.

Print in support that has the same density as the extruded material is the technique that lies behind the NSTRMNT 3D printer (figure 25). This printer prints in a gel that has the same density as the filament. After all the filament is in place an UV light is used to cure the light sensitive resin. Because the resin is injected in the gel and the pump can also be used to suck, it is possible to remove material as well. This allows the user to print and draw in real time. Complex forms will limit the possibilities of removing material as adjacent filament can hinder access to the place where the material removal is desired. Scooping out a part of the gel allows the removal of extruded filament in a more drastic way.

The gel can be reused over and over since it does not react with the resin during curing. The technique is a two phase production process since a print chamber has to be filled with support gel before extrusion can take place, but does not negatively influence the sustainability of the process, since the gel is reusable.

Both processes allow a six axis processing of the filament. The way of curing determines whether support material is needed or not. If liquid support material is used the chamber is directly related to the possible element size. Printing without is more flexible in this perspective.

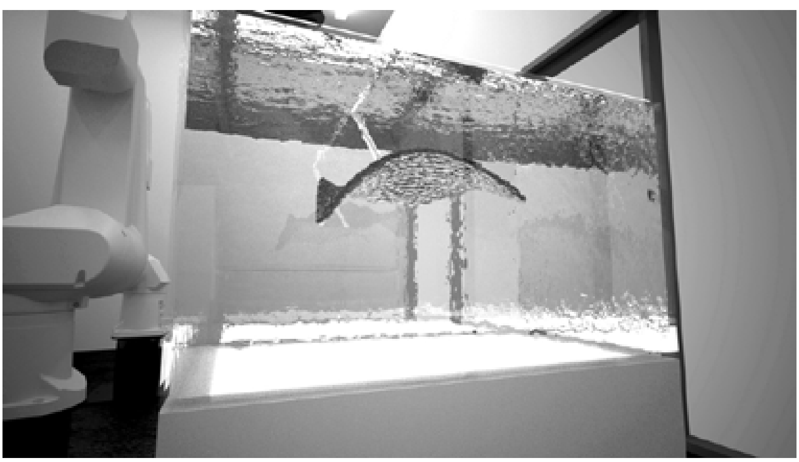


Figure 25 - NSTRMNT 3D-printer (1)

1 NTSRMNT, 2015

§ 3.3 *Moving formwork*

Climbing formwork is actually a slow concrete extruder. It is a technique that uses its formwork as a moving curing facility. After the concrete has cured, it climbs upwards to support new concrete (figure 26 and 27). The formwork acts like a nozzle would. This particular extrusion process is not a continuous process but merely a process with stages (figure 28). Since the formwork is standardized, but also able to be changed within the system, it can be considered simultaneously as a changing mould (§6.2.2).

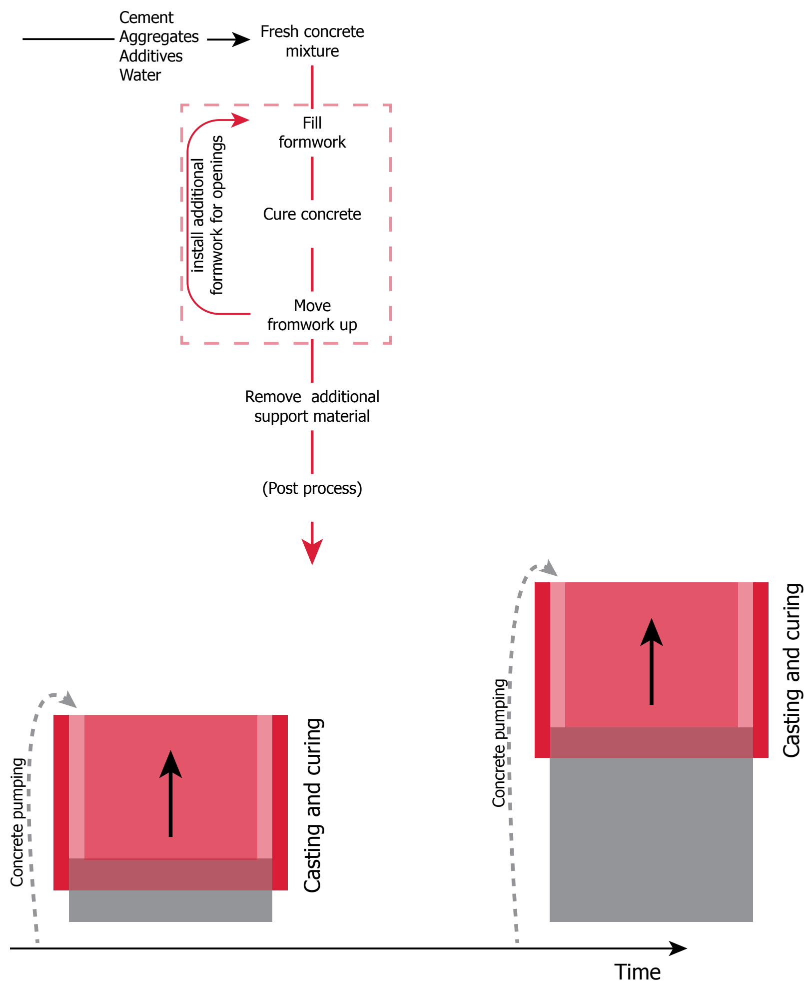


Figure 26 - Climbing formwork

Hollow core slab floor elements are made in a similar way. The concrete with very high green strength is extruded through a horizontal moving die. The die can be seen as the very temporary formwork. The concrete's strength is instantly high enough, allowing the extruder to propel itself against the extruded concrete.

Figure 27 - Climbing formwork [1]

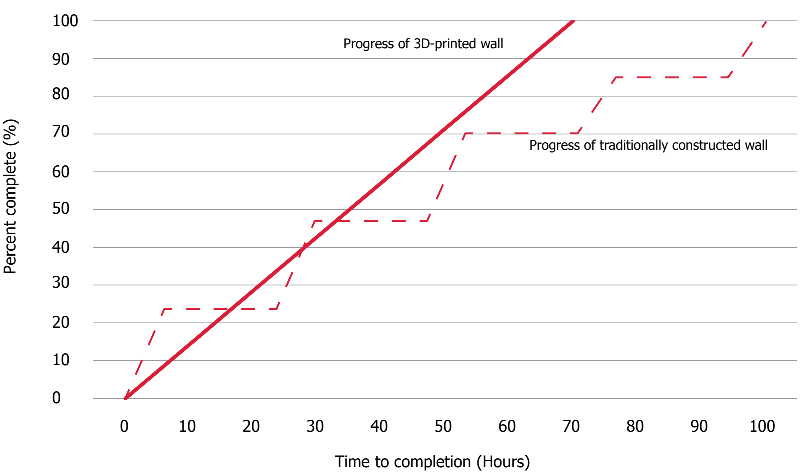


Figure 28 Time of completion [2]

[1] Skyscrapercity, 2009
[2] Adapted from Buswell, et al., 2007, p.230

§ 3.4 *Properties of AM*

AM has next to its advantageous properties also disadvantageous properties. It has threats and weaknesses. Table 12 shows an SWOT analysis based on Volkers, 2010. The weaknesses can be eliminated when the AM techniques evolves. For now the properties that are important are the accuracy, the finishing, material properties in the produced element and the production time. As long as other production technologies can produce better and more economical, while these weaknesses of AM are not solved, they form next to the limited size and mass production large threats for the AM technique.

In all AM processes the resolution is a dominant factor. An digital model is divided in surfaces before it is manufactured. During manufacturing the resolution determines the smoothness of the object. Figure 29 shows the relation between the digital model and the AM element.

AM is also capable of producing elements that cannot be made elsewise with the same ease as in an AM process. Complex forms without formwork or moulds are an example. In most of these processes the production of the mould is the most expensive stage in the production. For such processes AM has a lot of potential. Minimised price, minimum waste freeform are promising characteristics. For the difficult elements AM has a lot to offer, for standardized elements it cannot compete with the quality and speed of automated processes yet.

Advantageous properties	**Disadvantageous properties**
Freeform	Resolution can be seen in the surface
Can be used without expensive moulds	Limited production speed
Digital model can be used directly	Can be expensive

Table 11 - Advantage and disadvantage properties of AM

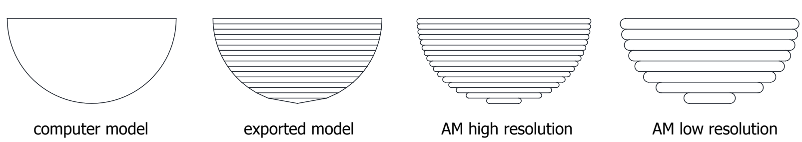


Figure 29 - From computer model to AM object in relation to the resolution

	Helpful	Harmful
Internal origin	Strengths Geometric freedom File to factory No tooling No inventory/labour costs Sustainability Freeform design Minimum waste Testing of unique products/certification Costs per piece	Weaknesses Production time Properties of materials/anisotropy Accuracy Finishing
External origin	Opportunities Mass customization Graded materials/Micro structures Printing composites Hybrid structures	Threats Limited size/Macro scale Mass production
	Helpful	**Harmful**

Table 12 - SWOT AM [1]

§ 3.5 *Sustainability*

As mentioned in the previous section AM is also more sustainable since no formwork is needed. To address the exact benefits of AM in relation to the LCA of the resulting products, intensive research is needed. For each product the LCA has to be calculated. Generally speaking it can be assumed that AM is environmentally more sustainable than a multiple phase production technique.

Since the AM technique uses a layered process, the characteristics of the products differ from the traditional ones. When considering sustainability, durability is also a parameter. If the lifespan decreases, the sustainability decreases. Evaluation of produced elements in comparison to known material characteristics is needed and already an ongoing topic. While the processes evolve, the durability of the products will increase and with that the sustainability.

§ 3.6 *Conclusions AM*

AM is a new and innovative technique that uses certain material characteristics in combination with a layered application process to build freeform objects. Its full advantage is when products can be directly produced from the digital model, with

1 Adapted from Volkers, 2010, p.18

minimum use of additional support material that will be wasted after finishing the object. The field of AM has been improved considerably. With simple desktop printers costing around a thousand euro's, a resolution of 0.02mm can be obtained (2015). Just a few years ago machines cost several thousand euro's and were not even able to produce objects with a resolution of 0.02mm.

4 Research definition

Over the last century the concrete industry has innovated considerably within their conservative framework (chapter 2). Several examples can be found in products that emerge from the demand of rational construction methods. These methods became interesting again and were re-developed to solve the shortage of houses in Europe during the post war period (Priemus & van Elk, 1971, p.15). Examples are:

- Lightweight construction systems

Reinforced prefabricated floor elements,

Reinforced prefabricated wall elements, and

Concrete masonry units.

- Tunnel and climbing formwork

The background on AM has shortly been discussed in the previous chapter. The problem statement and the emerging sub-questions related to processing concrete will be presented in this chapter. After the research is delimited, the existing AM techniques are enumerated with their properties in the next chapter (chapter 5).

§ 4.1 *Problem statement*

The architects and structural engineers design freeform elements in buildings. The production techniques for such forms is not synchronised to the ease that they can be designed (*Buswell, et al., 2007, pp.224-225)*. Rapid manufacturing can be a solution, but how should a liquid material like concrete, that needs curing, be handled. Studies related to the field of AM of concrete exist already.

Heads of state already refer to this new state-of-the art processing technique as one that will revolutionize the way products are made. It has the potential to change how the production facilities look like next to its capability to produce almost everything. (Gross, 2013). The challenge is how these new techniques should be implemented in the construction industry and how they should look like in case of concrete processing.

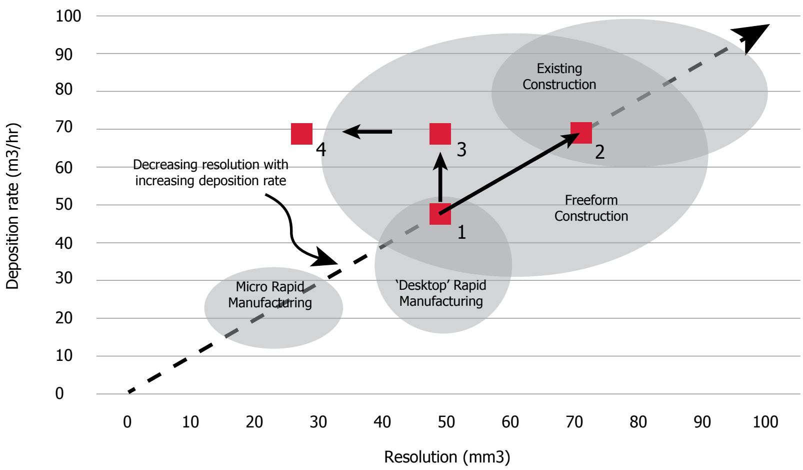


Figure 30 - Resolution/deposition paradox [1]

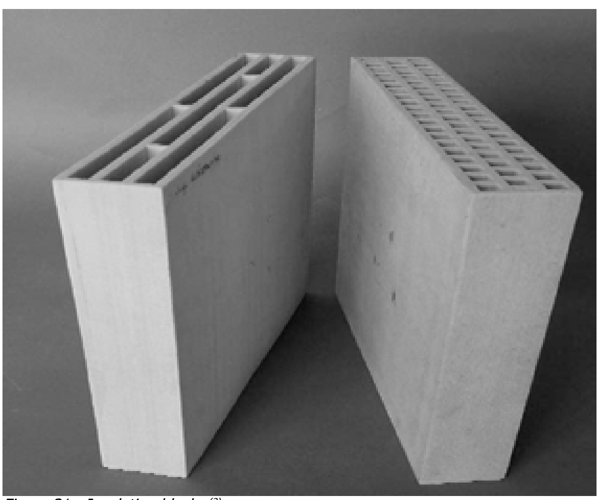


Figure 31 - Insulating blocks [2]

[1] Adapted from Buswell, et al., 2007, p.229
[2] Buswell, et al., 2007, p.230

§ 4.2 *Hypothesis*

Buswell, et al. (2007, p.229) show in their article a picture with the resolution / deposition rate paradox (figure 30). They assume that the desired location of rapid manufacturing is number 3 instead of where it currently is, number 1. An increase in speed, without a decrease in resolution, makes the freeform construction process more beneficial and more competitive. This assumption neglets that other ways of

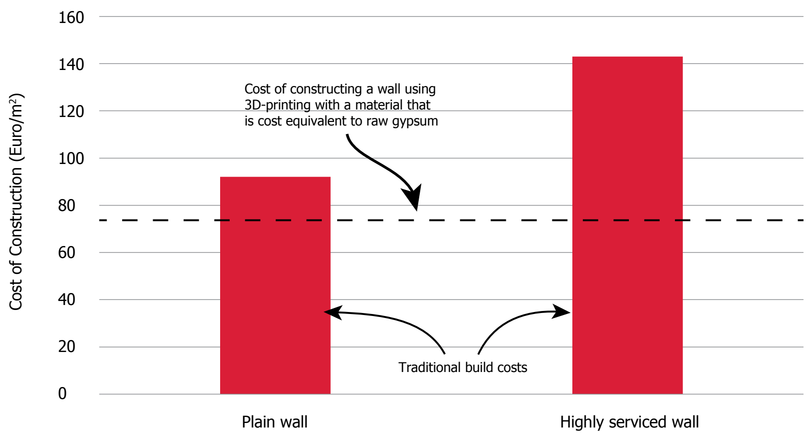


Figure 32 - Costs of printed wall [1]

processing can tackle the resolution problem by direct post processing. Number 4 indicates such a position with an increase in resolution and speed.

Depending on the used AM technique, the speed can be increased with an unchanged resolution untill certain limits. These limits can logically be found in the speed of an extruder’s head, or by the technique used to apply the binder in a 3D-printing or the materials in a polyjet process.

The AM process for the construction industry can be compared to other industries. The production of a book for example. Using an ink-jet or laser printer several copies can be printed at home. If an edition involves larger series, like standardised building elements, a more economical technique at a printing office is preferable. In the construction industry an in series produced hollow core slab is cheaper than a single floor that is casted in situ.

[1] *Adapted from Buswell, et al., 2007, pp.229*

The hypothesis related to the AM of concrete is:

AM of concrete should only be used for elements that actually benefit from this production process, either in the characteristics of the emerging products or by the economical benefits of an AM production technique.

Figure 31 shows a complementary product that an AM process can print. Panels with different characteristics regarding mass and thermal insulation can be produced like shown in figure 33.

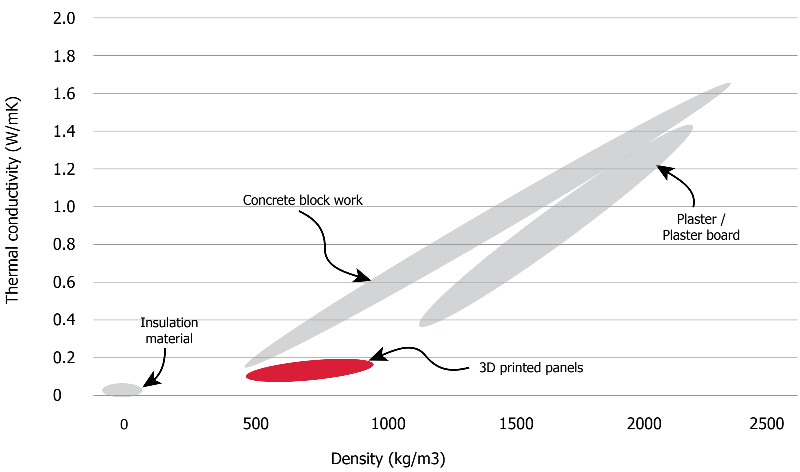


Figure 33 - Thermal conductivity (1)

§ 4.3 *Research questions*

The research question and sub-questions that have emerged after investigating the current concrete processing techniques and available AM techniques are:

"What are the conditions, regarding production techniques and form, to benefit optimally of an AM process for producing concrete façade elements?"

1 Adapted from Buswell, et al., 2007, p.230

Sub-questions that emerge can be split in two categories:

Current AM techniques in the concrete industry:
- What are the current concrete AM processes (2014)?
- What kind of products are made with the current concrete AM processes (2014)?
- What are the characteristics of concrete elements made by using an AM process?
- What is the definition of concrete used in such additive manufacturing process?

Evolved processing techniques:
- For what kind of façade elements is concrete AM the best production method?
- How should the concrete AM processes look like and evolve for façade elements?
- Should an AM process of concrete take place at the construction side?

§ 4.4 ***Research purpose***

The purpose of the research is to provide a good impression of the current state of AM regarding the processing of concrete. This will serve as reference and starting point to investigate the future possibilities of processing concrete. The hypothesis has been formulated to delimit the scope, but leaves some space for a search to an improved or evolved technique. After answering the questions, conclusions will be drawn on how concrete will be processed in the near future and the next decades. Recommendations, concept techniques and product ideas are the main goal of the project.

§ 4.5 ***Research methodology***

To answer the research questions the methodology will consist of a mixture of a literature review and empirical research.

Before an in depth discussion can take place, it is important that the material characteristics of concrete are known and kept in mind. In contrast to plastic, the behaviour and processing techniques of concrete are less well-known outside the discipline of civil engineering. A chapter on concrete has been included (chapter 2), to provide some basic information on concrete and as a reference.

Identification

In order to arrive at a point from where the possibilities of additional AM techniques for concrete can be investigated, the identification of the current situation of this technique is required (2014). Literature will be used to:

- Identify stakeholders,
- Present the current technical situation, and to
- Enumerate the properties and characteristics of the existing AM processes.

Theoretical research

In the theoretical research section, the properties of AM concrete will be examined in relation to the existing production techniques. The emerging products will be discussed on the basis of literature. This will show;

- The characteristics of elements made with the existing AM techniques, and
- The match or mismatch that may be present between the design and construction techniques.

The mismatch is interesting because, if a product can be made with a substitute production method (that already exists), AM has to compete with it. The only manner to keep a new production technique running, if it is not as cost effective as the competition, is by using it for complementary products. Matching products and production techniques need to be well considered to prevent a mismatch.

Research model

After the current techniques are analysed new production techniques, that cope with a certain absence in an existing concrete AM technique, have to be invented. The ideas for such machines will be presented. The ideas will be analysed and partly tested by making a small mock-up. The mock-ups will be used to demonstrate and analyse their potentials.

The results are evaluated and compared with expected future demands. By using literature and by investigating the capabilities of the newly introduced production techniques, an estimation to show the importance of evolving the AM technique for processing concrete will be made.

The thesis is split into two parts. The research is presented in the first part and shows the developments in the concrete industry, the match and/or mismatch between the design resources and a discussion of the production techniques. The second part introduces new processing concepts, followed by some appendices that show some experiments in more detail.

§ 4.6 *Scope*

The goal of the research is draw conclusions related to the AM of concrete with the help of a design. This will take place in the following framework;

After the literature research, future visions regarding AM and comparisons between various techniques are illustrated. This evaluation shows the relations between;

- Consistency
- Surface quality
- Strength
- Usability
- Added value (integration of parts and services, material use, form)

A roadmap will be used to summarise and show the potential of AM for processing concrete.

5 Concrete AM techniques

There are several studies regarding the AM of concrete. Before recommendations can be made it is important that the current situation is identified. This chapter will introduce, describe and discuss these studies. The points of improvement discussed in §5.8 will be used for recommendations, which are used to come to new printer concepts (chapter 7).

§ 5.1 *Concrete as AM material*

Concrete AM is a spin off of 'normal' AM. The main difference is that the materials that are used for AM techniques like plastic and steel are homogeneous and can easily be 'instant dried'. Concrete behaves differently. There are multiple concrete types. For extrusion processes, like FDM, a dense, rapid curing, mixture is used. In a 3D-printing process fine powder is used that needs to be bound by a liquid. Figure 34 shows the basic characteristics of three concrete AM processes.

In addition to the research departments at different universities, companies start to develop AM techniques for processing concrete themselves. Although they are based on techniques that are already introduced, they can evolve / change rapidly, by an investment in the private sector. The scientific research can move to the R&D departments of multinationals, which can bring momentum in the development. An example is Winsun new materials, a company in China. They claim to be the first to be able to print up to ten houses in 24 hours (figure 35), although the technique used looks like a less advanced copy of Contour Crafting (one of the initiatives in concrete AM at the University of Southern California).

Challenging is the material processing mechanism for concrete, as can be seen in table 13. The concrete is not instantly cured like plastic is after application of it.

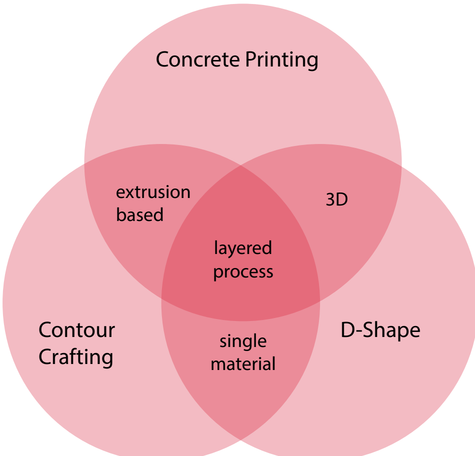


Figure 34 - Concrete AM techniques and their properties [1]

Figure 35 - Printed concrete house [2]

1 Adapted from S. Lim et al., 2012, p.264
2 Pei Xin/Xinhua Press/Corbis. (2014)

Mechanism	Constituent material	Composite
Phase change	Steel Plastics	
Drying	Clay	
Chemical bonding	Gypsum	
Instant chemical reaction	Cement	Concrete
		Smart materials

Table 13 - AM material processing mechanisms

§ 5.2 *Identification of stakeholders*

The stakeholders can be divided in research institutes (like universities), companies and persons that are involved in fields related to the AM technology.

Research institutes

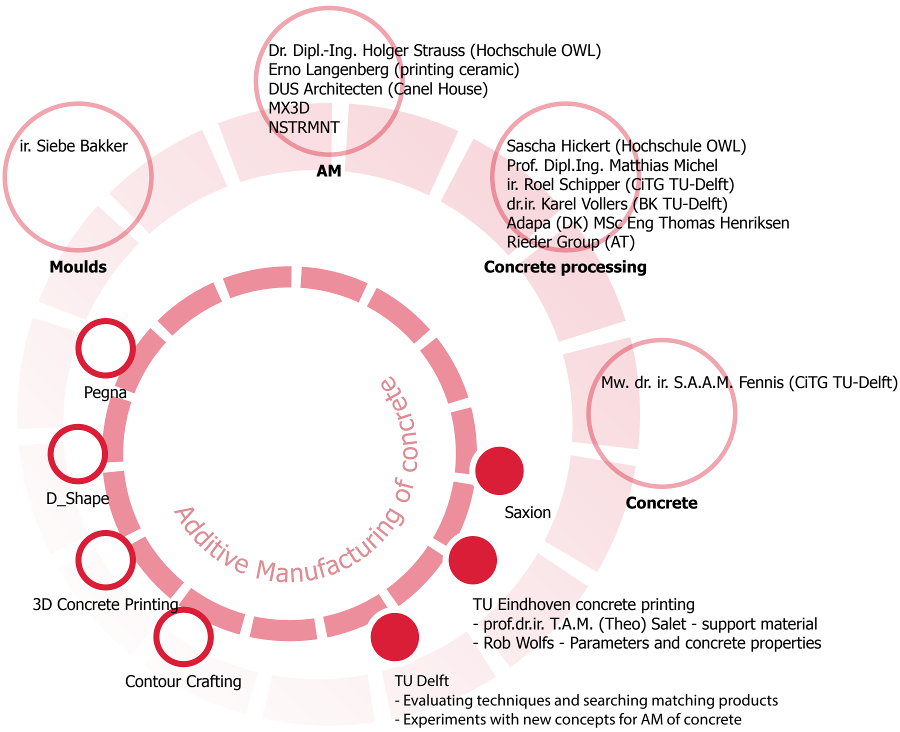
The stakeholders in the AM of concrete are presented in figure 36. There are evolved projects shown in literature, like Contour Crafting, 3D-Concrete Printing, Pegna and D-Shape.

Additionally there are new studies initiated. TU-Delft is not the only institute researching AM. At the Eindhoven University of Technology a thesis is being written about parameters that are involved in AM of concrete. With these parameters the researchers want to predict whether it is possible to produce an element with a certain fresh concrete mixture or not.

Other useful knowledge can be gathered from people in the disciplines of AM, concrete processing and concrete technology at the different chairs of the universities, but also from individuals working in fields related to AM.

Companies

As mentioned in the introduction, companies can start to play a major role. There is considerable knowledge available at the companies and they can more easily invest in new techniques by allocating their profits to R&D. One specific company, Winsun new materials, printed the houses mentioned previously. In France, EZCT, an architectural office, is experimenting with AM of sand moulds, to cast elements with UHPFRC (figure 37 and 38). Additionally the first AM machine that uses FDM to process concrete, the BetAbram, can be bought since a few months.



Companies
- Winsun New Materials - prints 10 concrete houses in 24 hours
- EZCT Architecture & Design Research - uses sand moulds for casting UHPFRC
- BetAbram - offers a FDM concrete printer

Figure 36 - Scheme of stakeholders

Figure 37 - Casted UHPFRC (1)

[1] Schwartz, 2013

§ 5.3 *Techniques*

Concrete printing processes can be used in different fields. Applications can be found in architecture and construction, arts and design and in the public domain (Lim et al., 2012, pp.262-263). There are different fields involved as indicated in the scheme of stakeholders. In the literature there are three interesting and well described AM techniques that are used for the AM of concrete.

There are also techniques that deform the concrete after it has been casted in a flexible mould. These kind of processes are performed by Adapa, a company in Denmark. However, by using the latter method the elements are just curved slaps, that become a 3D form. Roel Schippers experiments with the same techniques at the faculty of civil engineering at the Delft University of Technology. In Detmold at the Hochschule Ostwestfalen-Lippe and now at the faculty of civil engineering at the Darmstadt University, Sascha Hickert experiments with moulds made out of cloth. This process looks like the inflatable mould mentioned before.

For now the focus lies on AM methods. Table 14 shows an enumeration of properties of the well described concrete AM techniques.

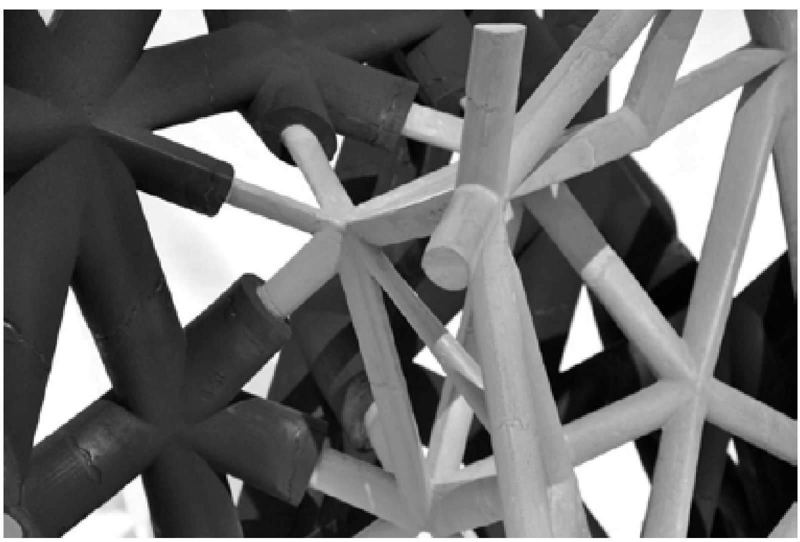


Figure 38 - Casted UHPFRC close up [1]

[1] Schwartz, 2013

Table 14 - Concrete printer technique properties [1,2]

	Pegna	Contour Crafting	Concrete printing	D-Shape
Process	3D-Printing	Extrusion	Extrusion	3D-Printing
Use of moulds	No	Yes (lost mould, becomes part of the component)	No	No
Build material	Sand	- Mortar mixture for mould - Cementitous material for build	In-house Printable Concrete	Granular material
Binder	Portland cement (activated by water)	None (Wet material extrusion and backfilling)	None (Wet material extrusion)	Clorine-based liquid
Nozzle diameter	1 mm	15 mm	9-20 mm	0.15 mm
Nozzle number	unknown	1	1	6300
Layer thickness	unknown	13 mm	6-25 mm	4-6 mm
Reinforcement	No	Yes	Yes	No
Mechenical properties	Tested with zero degrees of layer orientation, which means the force was given from the top of the printed surface			
Compressive strength	28.30 MPa	18.6 MPa[2]	72-110 MPa[i]	235-242 MPa
Flexural strength	14.52 MPa	unknown	12-13 MPa	14-19 MPa
Print size	>1 m dimension	>1 m dimension	>1 m dimension	>1 m dimension
Surface qualty	-	smooth	layered	layered
Use of materials	Optimal	optimal	optimal	optimal
Print speed/resolution	-	High	Low	Low
Pre/Post processing	Removal of unused material	- Reinforcement per 125 mm vertically - Backfill the mould with a cementitious material per 125 mm height - Smooth surface by trowel	Reinforcement after printing	- Compression of the powder for next layer by a roller with light pressure prior to the deposition - Removal of unused material
Pros	First attempt for freeform construction	Smooth surface by trowel	- High strengths - Minimum printing process; deposition & reinforcement	High strengths
Cons	- Massive material placement - Removal of unused material	- Extra process (moulding) - Weak bonding between batches due to segmented backfilling batches by one hour interval	- Limited printing dimensions by the printing frame, (5.4 m (L) x 4.4 m (W) x 5.4 m (H)	- Slow process - Rough surface - Limited printing dimensions by the printing frame - Massive material placement - Removal of unused material

[i] Depending on the type of fresh concrete and used additives

[1] Adapted from S. Lim et al., 2012, p.264
[2] Added information from Hwang, 2004, p.4

§ 5.3.1 *Contour crafting*

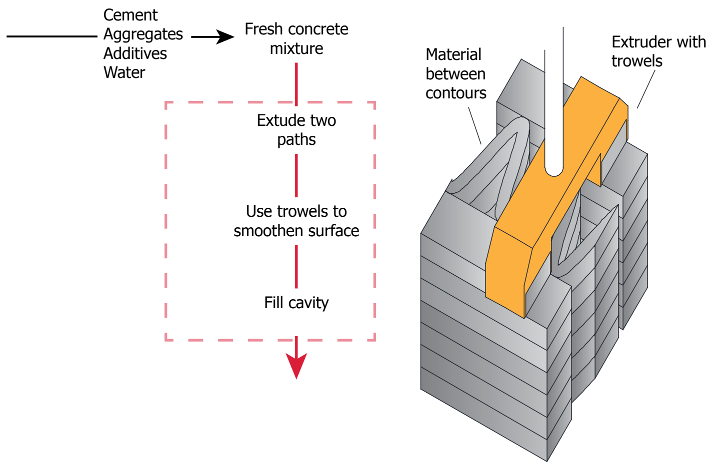


Figure 39 - Schematic visualisation of Contour crafting

Contour crafting is a process that extrudes a mortar mixture. The mortar is extruded and a trowel is used to get a smooth surface (figure 39). The process has been evolved over the years. A second trowel was added to smooth the surface even better, where after two extrusion heads were used to extrude just the contours of the designed element. A third extruder to cast concrete between the built walls was added. Additionally, experiments with different materials, heating and / or moisturizing the surface were done to improve the surface quality.

Extruding between the trowels is just a part of the contour crafting concept. Next to the AM of the concrete, other operations can be integrated. As the words Contour Crafting already says, it is crafting the contours, done by extruding between the trowels. This is comparable to a potter who forms the contours with his hands (Khoshnevis, Bukkapatnam, Kwon, & Saito, 2001, p. 39). The main idea is to print the contours and use the space in between to be filled with other materials. Insulation is one of them but for structural strength it can be filled with concrete as well. Experiments with reinforcement elements have been done to gain more resistance against tension forces (figure 41). Another possibility is to integrate pipes and wires (figure 42). All these concepts are shown in Khoshnevis's article Automated

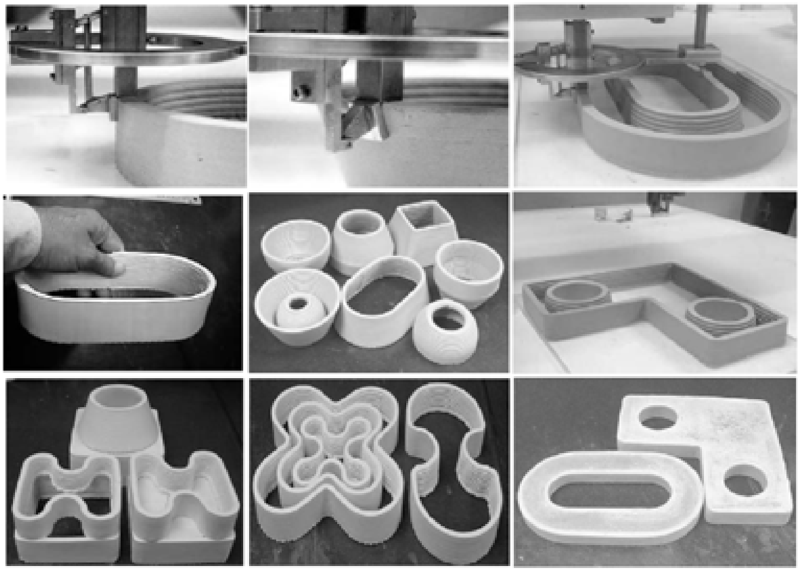


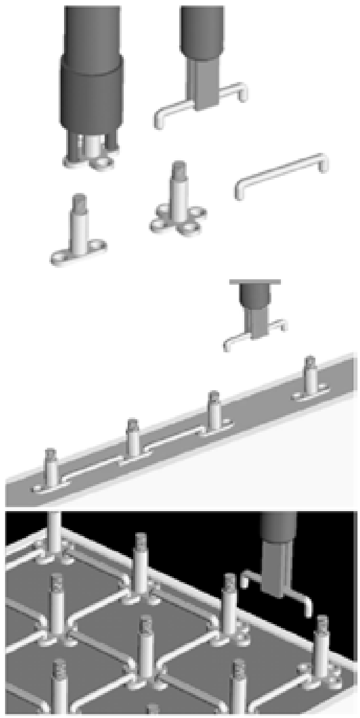
Figure 40 - CC in operation and representative 2.5D and 3D shapes and parts filled with concrete [1]

construction by Contour Crafting related robotics and information technologies. It discusses complete buildings with the use of Contour Crafting for the walls and pre-casted beams to support the floor elements. The system becomes an automated robot that is able to do multiple operations at once that normally have to be done by multiple machines (figure 43).

Contour crafting is also investigating the feasibility to facilitate the technical knowledge to build for extraterrestrial applications. The idea is that local materials are used as a mortar for in situ extruding a lunar base (Khoshnevis, 2004, pp.17-18). In 2013 NASA funded a study after evaluating the technique in 2010.

The compressive strength of the Contour Crafting elements is around 18.6 N/mm^2 (Hwang & Khoshnevis, 2004). This will be considered as one of the weakest concrete classes (table 17), but is still widely used in the construction industry, because higher compression strengths are accompanied by increased tension loads. To withstand these tension forces in the concrete extra reinforcement is required.

[1] Khoshnevis, 2004, p.12



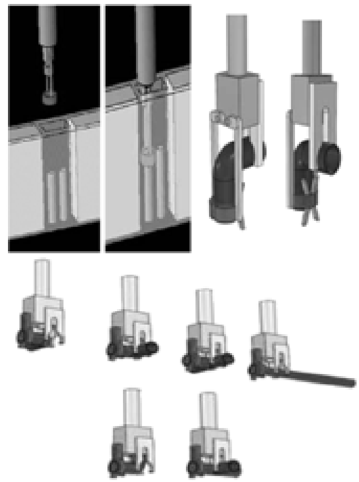


Figure 41 (left) - Reinforcement components and assembly procedures for walls and columns [1]

Figure 42 (right) - Plumbing modules and grippers [2]

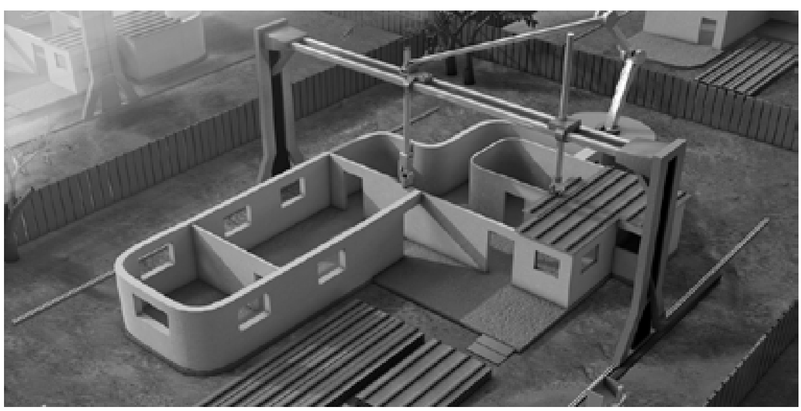


Figure 43 - Construction of conventional buildings using CC [3]

[1] *Khoshnevis, 2004, p.7*
[2] *Khoshnevis, 2004, p.8*
[3] *Contour Crafting, 2015*

Type II hydraulic Portland cement	4.31 kg
Sand	4.76 kg
Plasticizer	0.36 kg
Water	2.18 kg

Table 15 - Mixture CC [1]

The mixture used contains a very high content of cement. In fact it is a mortar, but they sell it as concrete. Table 15 shows that the mixture consists of cement and sand with a plasticizer to increase its workability.
The WCR is 0.51 which will cause capillary voids within the hardened concrete. The ratio between sand and binder is 52 : 48. Compared to regular concrete with a ratio of 17 : 83 this is relatively high. The high amounts of especially Portland cement will cause a lot of internal shrinkage in concrete. Not just because of the reaction causes shrinkage, but also due to the expansion and shrinkage caused by the heat of the exothermic reaction.

[1] *Hwang, et al. 2004, p.4*

§ 5.3.2 *3D-Concrete printing*

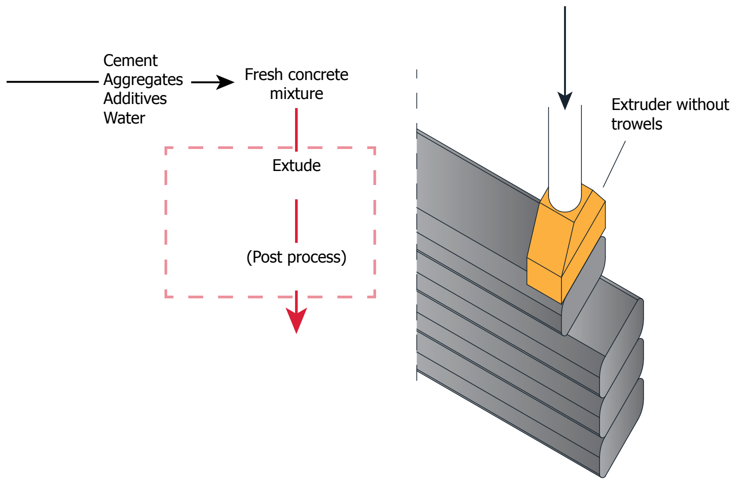


Figure 44 - Schematic visualisation of 3D-Concrete printing

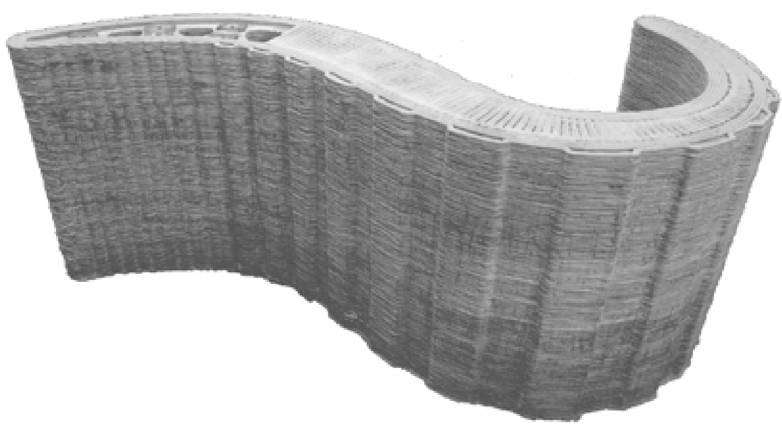


Figure 45 - Bench made with 3D-Concrete printing [1]

[2] *Domus, 2014*

3D-Concrete printing is an extrusion process without trowels. The surface of the extruded concrete is rough (figure 44 & 45). The techniques differs from Contour Crafting, but exhibit also similarities, as can be seen in table 14.

The compressive strength is between 72-102 MPa, flexural strength between 6-17 MPa and tensile strength between the layers between 0.7 and 2.3 MPa depending on the speed of extruding and the time to cure in between. There are less voids in comparison to casted concrete, 1.0% instead of 3.8%. Due to the higher density the printed concrete has a density of 2350kg/m^3 instead of 2250kg/m^3 when the same fresh concrete mixture would be casted. Poor AM concrete gives 4.8% as can be seen in figure 46 and 47 (Le, Austin, Lim, Buswell, Law, et al., 2012a, pp.561-564). The voids will, like capillary voids, weaken the concrete's strength significantly (table 4). Also 3D-Concrete printing uses a mixture that contains a large fraction of binder. The silica used is also a binder like cement. The sand binder ratio is 60:40 (table 16).

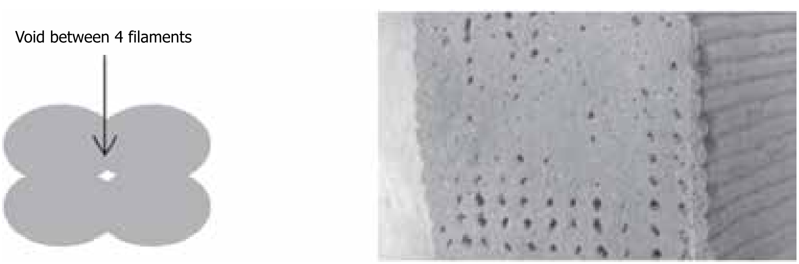


Figure 46 - Voids between printed concrete (concrete printing) [1]

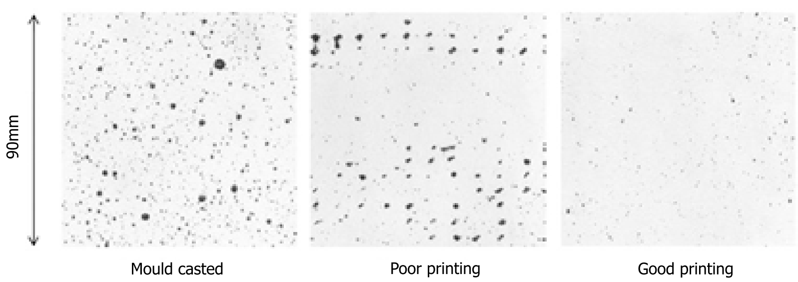


Figure 47 - Mould cast poor and goodprinting structure [2]

[1] Le, et al, 2012a, p.559
[2] Le, et al., 2012a, p.562

Material	kg/m^3
Sand	1241
Cement	579
Fly ash	165
Silica fume	83
Water	232
12 / ø 0.18 mm polypropylene fibres	1.2
Super plasticiser	1%
Retarder	0.5%

Table 16 - Mixture 3D-Concrete printing [1]

§ 5.3.3 *D-Shape*

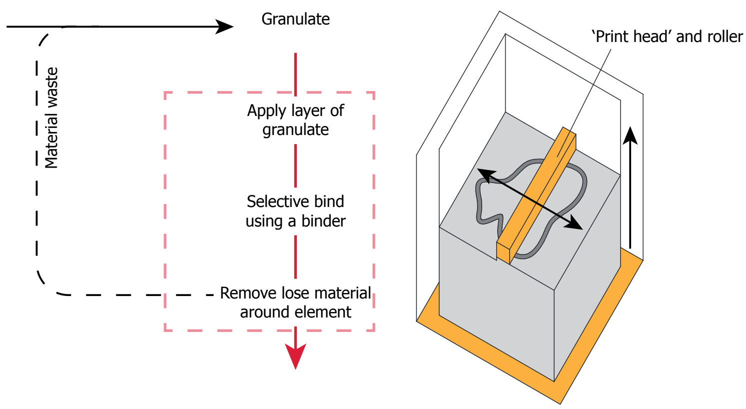


Figure 48 - Schematic visualisation of D-Shape

D-Shape is a process that uses a granular material (sand and stone powder) and a chorline-based liquid as binder. The granular is used to build the form but also as support material. This 3D-printing process presents the opportunity to make complex forms. During the printing process a new layer of granulate has to be applied on the complete print area. This is relatively time intensive (Lim et al., 2012, p.264). When the model is finished the powder has to be removed. Internal voids are filled with powder if no measures are taken (figure 49).

Like NASA that supports Contour Crafting, ESA is interested as well in AM, to build

[1] *Le, et al., 2012b, p.1227*

a lunar base. ESA works with Foster+Partners and use Enrico Dini's D-Shape to explore the possibilities for a lunar base. The designed dome is supported by a catenary wall element, which is reminiscent of a bone structure (figure 50) (ESA, 2013).

Figure 49 - D-Shape removing the material that has not been bound [1]

Figure 50 - Lunar base by Foser+Partners [2]

[1] Materia, 2013
[2] ESA, 2013

§ 5.4 *General product properties*

The most used technique to make concrete elements is casting and in these processes different mixtures are used. In AM of concrete this is limited due to the fact that a mixture with a certain fluidity combined with some firmness is needed. Reinforcement is also a challenge. For example the way the material is processed with the current methods causes that reinforcement cannot be placed before printing, but has to be placed at a different moment and in a different way, during or after the element has been printed.

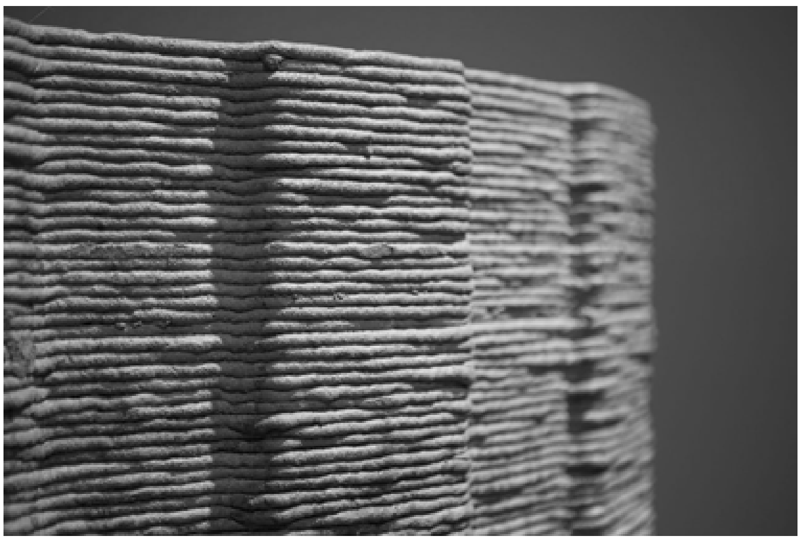


Figure 51 - Surface 3D-Concrete printing (1)

1 Domus, 2014

§ 5.4.1 *Mixtures*

The mixture is crucial and determining factor. A simple experiment performed at the faculty of civil engineering showed that there is a relation between the strength and the way the concrete was processed. Three different samples were casted and tested;

- An element that was compacted at once after casting,
- An element that was casted out of five layers, that were applied with 5 minutes time intervals to simulate a printing process, and
- An element that was compacted after it had been casted out of five layers, that were applied with 5 minutes time intervals.

The element that was casted at once and compacted was the strongest, followed by the layered compacted sample. The strength was respectively 28.58, 28.41 and 23.2 MPa for the not compacted layered sample, after 7 days of curing. Appendix 1 shows the complete experiment.

If the concrete is additive manufactured with selective binding like 3D-printing, the capillary action is important. The selective binding relies on the accuracy of the applied binder. If the binder flows out to the surrounding material, the resolution decreases and the concrete will not be hydrated completely.
Since the selective binding method uses an additional adhesive instead of cement to bind the materials together, the concrete mixtures characteristics mostly only apply for extrusion processes, that use actual concrete.
The composite that is referred to as concrete consists of three different material categories, the binder, the aggregates and the additives. Each with their function. The ratio of them in a mixture that is used for AM, can be changed to obtain the desired mixture.
In casting and spraying concrete (shotcrete) the ratios are used to obtain;

- A certain strength,
- The concrete characteristics regarding durability, sustainability and resistance against environmental influences, and
- Workability.

The concrete is pumped through pipes and extruded trough a nozzle in case of an extrusion process. Therefore the processability is, next to the strength and the characteristics of concrete, very important in an AM process. The shear strength during processing and the open time of the mixture is of high importance. Those two

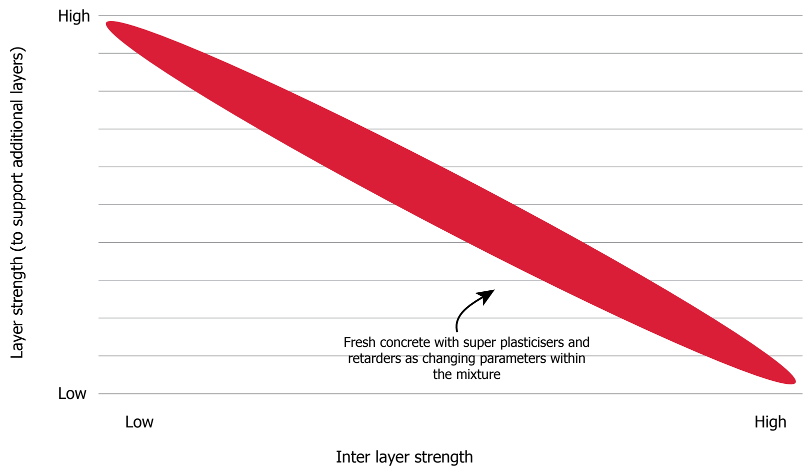


Figure 52 - Open time, workability and inter layer strength

parameters can be controlled with;

- The water cement ratio,
- The aggregates, and
- Additives like super plasticisers and retarders.

Contour crafting uses a mixture that is shown in table 15. The mixture used by Loughborough University for the 3D-Concrete printing can be found in table 16.

$$f'cn = a \cdot N_n + \frac{b}{wcf} - c$$

For CEM II 52.5

$$f'cn = 0,85 \cdot 61 + \frac{33}{0.4} - 62$$

$$f'cn = 72 MPa$$

When Loughborough's mixture is calculated with a standard formula the strength differs to the measured strengths in table 17. This has to do with the high ratio's of cement and the processing technique used.

Loughborough tested also the workability and the open time of the mixture. To be able to process the mixture through, in their case, a 9 mm nozzle, the shear strength of the mixture should be between 0.3-0.9 kPa to have a workable mixture that is not too wet or too dry. Too wet will lead to filament that it is not able to support layers above and a mixture that is too dry will cause the the filament to break easily (Le, Austin, Lim, Buswell, Gibb, et al., 2012b, pp. 1226-1231).

The knowledge about concrete mixtures, inter layer strength and green strength is available, it only needs to become available for AM processes. 3D-Concrete printing uses a UHPFRC. The mixture contains a relatively large amount of cement, but maybe that is not even necessary for all aplications. The sand binder ratio is 60 : 40. This can also cause a lot of inernal shrinkage and heat in case of Portland cement, with the possibility of an exceedingly amount of cracking. More information about desired mixtures for an AM process is enumerated in § 7.1.

§ 5.4.2 *Reinforcement*

Reinforcement in traditional concrete is embedded to distribute the tension forces. In additive manufactured concrete it has, if short fibres are used, also the ability to hold the mixture together during extrusion and curing, because it makes the mixture less fluid and provides more green strength. The process does not allow fibres between the layers. The fibres are just in the layers but do not take part to increase the interlayer strength.

Reinforcement used in the 3D-Concrete printing technique is 12/0.18Ø mm polypropylene fibres (Le, et al., 2012b, pp. 1231). Because of limitations regarding the size of the nozzle, the not aligned reinforcement fibres have to be short. Manual applied reinforcement can be used between all layers, by leaving openings in the printed concrete. Afterwards the reinforcement can be placed in these openings to pre-stress the printed concrete. This has been demonstrated in the bench made with the 3D-Concrete printing technique (Lim et al., pp.266-267). The bars used to pre-stress the concrete have to be protected and / or covered, because otherwise due to corrosion the element can be damaged.

	Fck,cyl [N/mm2]	**Fck,cube [N/mm2]**	
C8/10	8	10	
C12/15	12	15	
C16/20	16	20	18.6 - Contour crafting
C20/25	20	25	28.30 - Pegna
C25/30	25	30	
C30/37	30	37	
C35/45	35	45	
C40/50	40	50	
C45/55	45	55	
C50/60	50	60	
C55/67	55	67	
C60/75	60	75	
C70/85	70	85	
C80/95	80	95	
C90/105	90	105	100-110 - 3D-Concrete printing
C100/115	100	115	
higher classes			235- 242 D-Shape

Table 17 - Concrete class properties

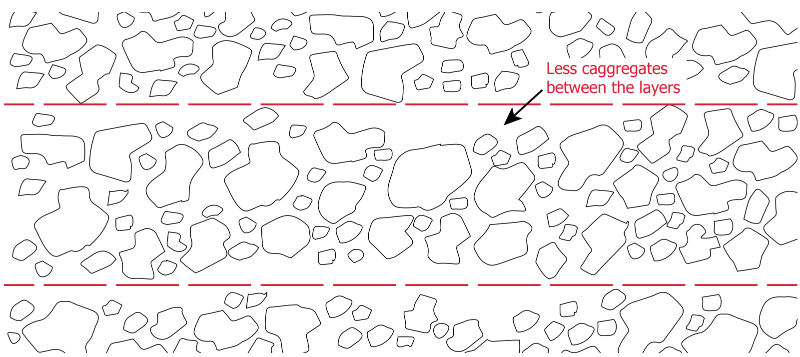


Figure 53 - Layers when aggregates used in AM concrete

§ 5.4.3 *Layered characteristics of AM*

D-Shape uses a process whereby the support of the bounded material is done by the powder underneath. This is one of the advantages of the 3D-printing process. It has the advantages of mouldless production and does not suffer under the disadvantage that AM techniques exhibit due to lack of support. Printing voids is nevertheless a challenge.

Contour Crafting and 3D-Concrete Printing extrude fresh concrete in layers. The bounding between the layers, influenced by the open time, is fundamental and determining the strength of the element (figure 53). D-Shape is the most isotropic because of the binder that is used.

§ 5.5 ***AM of concrete***

Additive manufacturing can be split in three trends Rapid Prototyping (RP), Rapid Manufacturing (RM) and Rapid Tooling (RT). RT and especially RM are expected to become very important in the building industry. The limitations nowadays are the limited size, accuracy, finishing and the material properties (Volkers, 2010, p.41). The SWOT analysis indicates the Strengths, Weaknesses, Oppurtunities and Threats. Bourell et al. (2009) describe two approaches. The approach to make existing products the same way but better or to produce products we only can produce by using the AM in a RM process. "In addition to the time-tested advantage of being able to create unique geometries, there are a host of other possibilities in varying degrees of maturity, including cellular structures, gradient structure, directional properties, on-the-fly in-build probing of the internal structure, etc." Trying to mimic products that are produced normally, creates an extra challenge for AM. It has to compete with the performance of existing methods (Bourell et al., 2009, p.20-21). If products are build that do not suffer from competition, it is more likely that a steadily improved AM process will succeed.

Complementary products are the best way to gradually improve and create new product types. On the other hand mimicking existing material properties is important as well, since understanding of physical properties and how they can be formed in an AM process will provide knowledge needed for improvement. The two approaches do not exclude each other but have to develop in such a manner that they consolidate.

For concrete this means that the properties need to be well investigated in relation to the AM techniques. What is going on during curing of concrete and how can it be controlled. The products as quoted can be more optimised like self-optimised three structures, instead of the massive sections used in elements nowadays.

§ 5.5.1 *Concrete products that benefit from an AM process*

What kind of concrete elements should be manufactured with an AM technique?

As discussed before and in §2.2 prefabricated concrete elements are produced highly automated and optimised. Generally there are several types of products as Eekhout (1997) mentions;

- Standardised products,
- Systemized standardised products,
- Standardised system products,
- System products,
- Special system products,
- Systemized special products, and
- Special products.

The AM technique should not be used as a substitution good of prefabricated elements, but as a complementary production method to produce special elements. The increase in performance of AM that can be expected will not be able to compete

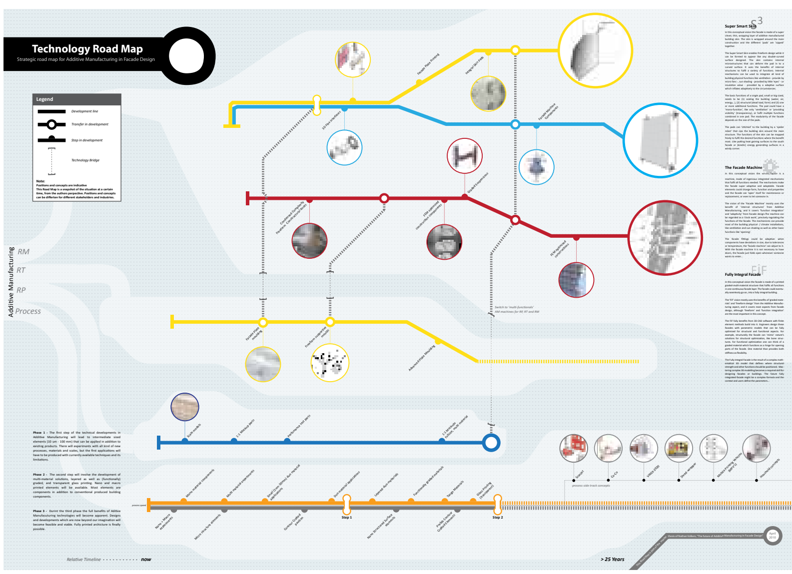


Figure 54 - Technology Roadmap by Volkers [1]

[1] Volkers, 2010, p.109

with the existing production techniques in an economical way, but are important to understand physical properties, as shown by Volkers's Technology Roadmap (figure 54 & Appendix A9). Therefore elements that can be produced with traditional automated and optimised production techniques should not be reproduced the next decades as mentioned before.

Products

The complementary production technique should focus on;

New product types;

- Products with internal holes that cannot be produced otherwise.

Special forms (special products) that are very expensive due formwork, these can be subdivided in;

- Connections between standardised prefabricated products,
- Individual products, or
- Small series.

Priemus et al. (1971) divides the construction industry by production methods. What kind of building techniques AM can be used for are indicated in red (figure 55).

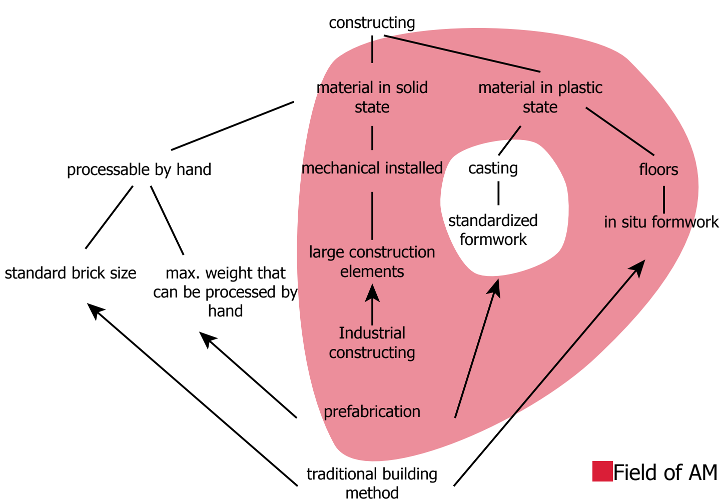


Figure 55 - Construction methods and the field where AM can manifest [(1)]

[1] *Adapted from Priemus, et al, 1971, p.10*

§ 5.6 *Environment: Material use, production and sustainability*

The building's components have different life spans (figure 58) (Brand, 1994, p.13). To compare products and the LCA's one can look at;

- Amount of materials used (optimisation),
- Material properties printing versus common techniques (e.g. structural performance),
- Embodied energy next to the product itself (transport),
- Casting and mould embodied energy versus printing energy, and
- Life span of the element.

The material concrete is new in the field of AM. Why would you print concrete instead of a plastic? Dus Architects is printing in a bio-based plastic and are searching to replace the plastic. Some experiments have been done with a cementitous granulate. Advantage properties for constructing can be found in the facts that;
Concrete has a higher density and fire resistance than plastic. The main advantages of concrete are its compressive strength, processability and the low costs. (Bio based) plastics are for that reason less suitable to act like a thermal buffer. In

Figure 56 - Kamerprinter at Dus Architects

Figure 57 - Printed element at Dus Architects

addition, concrete can be considered more durable and because of thermal buffering capacities it can be considered, due to the lower energy demand to maintain a stable temperature, more suitable for indoor constructions in daily used buildings.

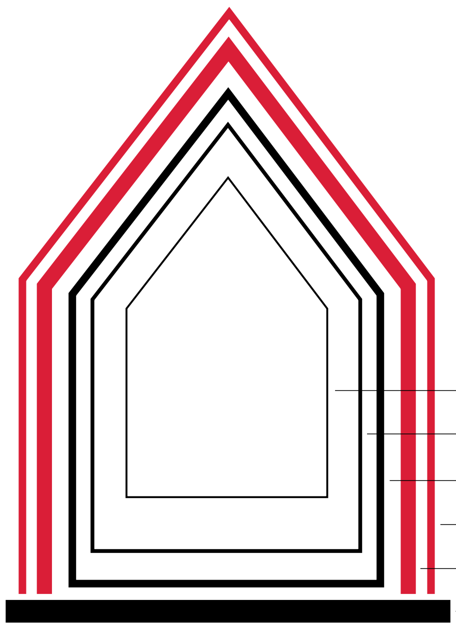


Figure 58 - Life span building components [1]

The embodied energy of concrete is relative low if compared to other materials (figure 59 & 60). Unfortunately recycling of concrete is hard. Alloys and metals can be recycled easily. To minimise the consumption of raw materials optimisation is desired for concrete structures.

[1] *Adapted from Brand, 1994, p.13*

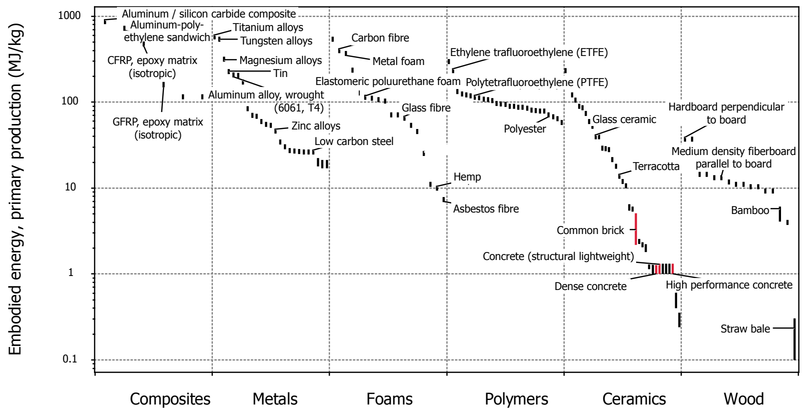


Figure 59 - Embodied energy/kg (MJ/kg) (CES)

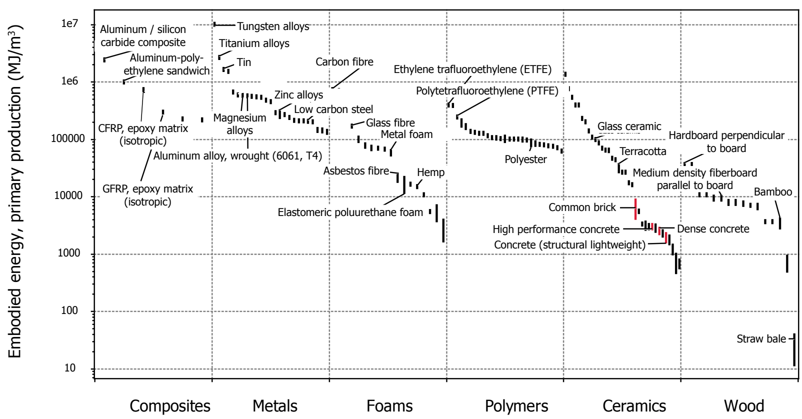


Figure 60 - Embodied energy/m³ (MJ/m³) (CES)

§ 5.6.1 *Material usage*

The amount of material used in an AM should be less than in a conventional process. The material properties of Contour Crafting and Loughborough University used do not match the desired characteristics in an element. Loughborough's mixture has a compressive strength of 110 MPa at 28 days (Le, et al., 2012b, p. 1231). The 40% binder in the mixture causes an increase in emission if compared to normal concrete that contains only about twenty percent cement. 110 MPa compression strength gives probabaly an over dimensioned element. In such a case the argument of material efficiency in AM processes is not valid anymore. Contour Crafting performs even worse if the structural strength of a 48 : 52 binder sand ratio gives only a compressive strength of 18.6MPa.

The expected strength of concrete, shown in the grey bar of figure 61, shows the expected relation between strength and the amount of cement. This needs to be changed otherwise AM concrete performs less on their LCA due to its high cement factors.

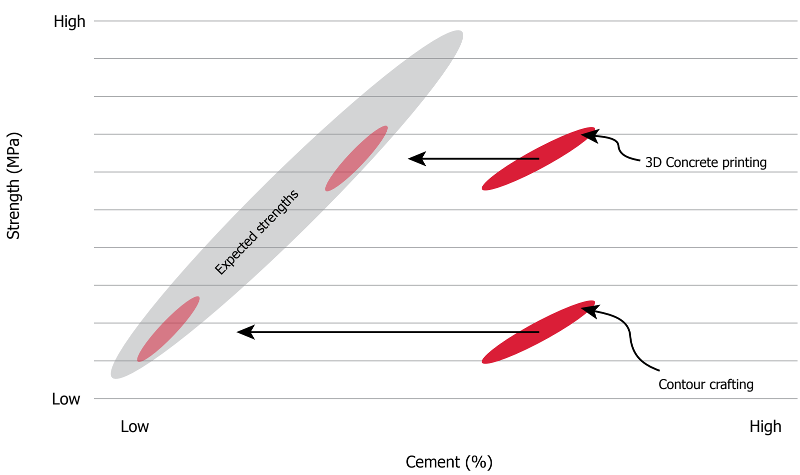


Figure 61 - Material usage compared to the expected strength

§ 5.7 *Evaluation*

Extruding with two extrusion nozzles, one with the final elements material and another one with support material, is a hybrid solution that creates extra formwork around vulnerable parts of the element. In the case where the formwork nozzle uses a reusable material, there is no embodied energy lost in the formworks material. This could be a new technique for processing concrete.

In the case of concrete in a 3D-printing process the cement should be bound by water. It will be very hard to regulate the process due to capillary working of the dry concrete mixture and the difference in aggregate sizes (Appendix A4). To print concrete that fulfils literature's demands, aggregates larger than sand should be used to comply with the condition that a large part of the aggregate has a >4mm diameter. To avoid problems with the 3-D printing process the resolution has to be bigger than the largest aggregate size. Printing smooth surfaces will become difficult if only layers are extruded on top of each other without direct postprocessing with for example trowels like used in Contour Crafting. This is the reason why the concrete used for AM needs to be defined. The aggregates are also in the layers and not between layers. An anisotropic layered material will arise, even if the inter layer strength between the layers is equal to the materials properties / strength (figure 53) since cracking happens at the bounding of the cement paste and the aggregate material.

Extruding concrete through nozzles causes a lot of friction and wear to the extruder. Decomposition of the mixture occurs which is probably the biggest problem (appendix A3). Fabricating hollow core slab floor elements, the concrete is extruded using a worm gear to compact and push the concrete through a nozzle. If a normal cylinder is used to extrude, the water is pushed out of the mixture. The worm gear prevents decomposing of the fresh concrete. The extruder moves because it is simply pushed away during extrusion. The extruded hollow core slab element is hard enough (has enough green strength) to cope with forces that are released. An advantage of this particular extrusion process is that the aggregates are distributed equally, as it is pressed through a die instead of a nozzle and because this slab is extruded in one single layer. A variable die might be an idea to make simple columns with changing sections.

§ 5.8 *Points of improvement*

Comparing printed and traditional in situ or prefabricated elements, some extremely crucial properties for concrete are missing in AM processes that use concrete;

- Substantial fraction of the aggregates >4mm
- Reinforcement
- Consistency
- Surface quality

To improve the usefulness of the AM process, the following three properties should be introduced for further investigation.

- Aggregates to decrease the costs, which is traditionally one of the strengths of concrete,
- Aggregates to minimise the internal shrinkage,
- Reinforcement to cope with tension forces,
- Consistency to cope with tension and bending forces. Since the consistency of the extruded filament has not changed compared to normal casted elements, the concrete processing by printing makes it anisotropic. An anisotropic material can be used and its anisotropy can be used in a beneficial way, but in that case the direction of the loads should be in the correct direction. It is preferable to eliminate the anisotropic behaviour because only than the widely used standard calculation methods can still be used, and
- Increased resolution to improve the surface quality.

In addition, other techniques and their advantageous properties can be combined with AM. For example, lost moulds that are put in AM concrete elements during fabrication as support and to facilitate internal voids. Multiple nozzles for different materials are not used yet. If an additional material can be extruded, the support can be build while the element itself is fabricated as well. In plastic AM this system already exist and examples can be found in FDM printers that with dual extruders. The kind of material used to build the support material influences the LCA of the production process.

§ 5.9 *Conclusions AM of concrete*

AM processes should not be used to replace evolved production techniques of standard elements. Elements that make use of the capabilities of AM in a beneficial way are a better option. Also because such a production process has not to compete against other, existing techniques.

Uniform concrete with substantial sized aggregates and eventual internal reinforcement is currently impossible to make. Other techniques to integrate them need to be invented or other ways of material processing should led to new design solutions.

Should AM adapt to our accepted way of designing or should our way of designing be adjusted to AM capabilities? Both are an option, but in that case compromises have to be made.

Production speed is limited by the speed of the extrusion head or nozzles in the roller. Building large objects will cost a lot of time if a high resolution, because of surface quality is desired.

The production techniques are important, but also the stakeholders. Two parties are involved;

- Designers that use the possibilities of these techniques
- Engineers that build new equipment

Comparing the roadmap by Volkers (figure 54 & Appendix A9) to the technical situation it is important that the AM of concrete keeps evolving. Before the desired elements can be made, experiments need to be successfully carried out. Logically, the start is always a simpler method and less complex regarding form. Now is the period that the parameters have to be established and simpler objects should be fabricated with the integration of some improvement. These improvements, like reinforcement, isotropic material and lower environmental impact by lowering the amount of cement in the fresh concrete mixture, increase the performance of the processes. When the processes will be able to print more complex forms the mismatch between technique and products also decreases.

6 Alternatives: other ceramic materials and threats

While concrete is a composite material according to the literature, one of the main materials in it, cement, is a ceramic. In addition to cement there are other ceramic materials used in the construction industry;

- **Clay structures**
- **Clay Bricks**
- **Sand- lime bricks**
- **Loam**

For these materials an AM production method can be almost the same as for concrete, i.e. support and workability of the material is still important, but due to different material properties and behaviour they are worth investigating.

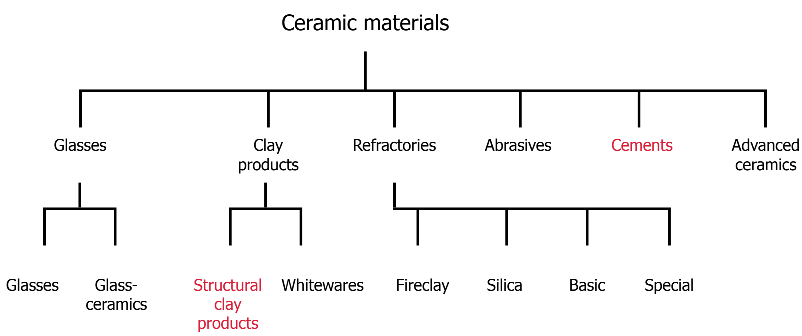


Figure 62 - Classification of ceramic materials [1]

The scheme above shows the classification of ceramic materials. The most interesting for the construction industry are cement and the structural clay products. Clay shows to be an alternative material, as well as threats for AM of concrete. Such threats for AM of concrete can be found in advanced formwork / moulding processes, that use AM in another way, but also from subtractive processing techniques.

[1] *Adapted from Callister, 2007, p.461*

§ 6.1 ***Clay***

Plastic clay, a composition called hydroplasticity, can be shaped due to the water molecules that covers the clay particles, which allow the layers of clay to move. Figure 63 shows the kaolinite structure of clay.
The more water applied the more shrinkage will occur during drying and firing (figure 13). If clay dries, it hardens but is still soluble in water. The green ceramic bodies that are formed can be fired afterwards. Firing is used to change the chemical bindings in the clay. One of the reactions, that take place during firing at temperatures between 900 and 1400 ^{0}C, is called vitrification. Small glass particles are formed. Figure 64 shows a micrograph of a fired specimen (Callister, 2007, pp.463-481).
Materials based on clay have a lot of matching characteristics with concrete. Figures 65 till 70 show that clay compared to concrete has a;

- Higher compressive strength,
- Higher tensile strength,
- Higher elastic limit,
- Comparable young modulus,
- Less thermal expansion, and
- Higher embodied energy is.

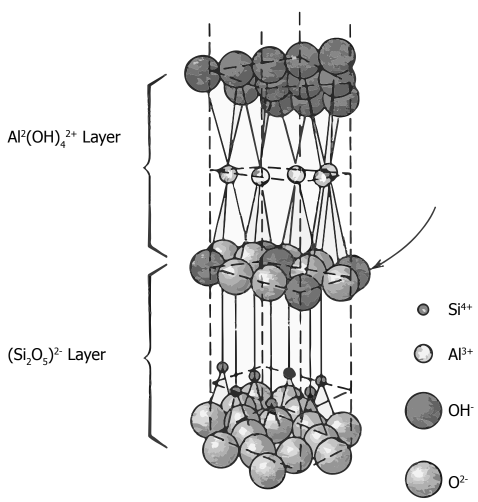


Figure 63 - The structure of kaolinite clay [1]

[1]*Callister, 2007, p.430 adapted from Hauth, W.E., 1951, p.140*

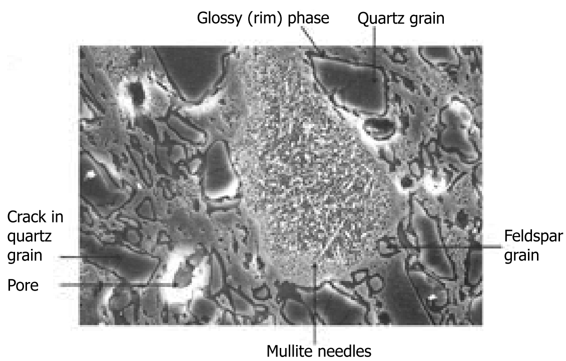


Figure 64 - Scanning electron micrograph of a fired porcelain specimen (1)

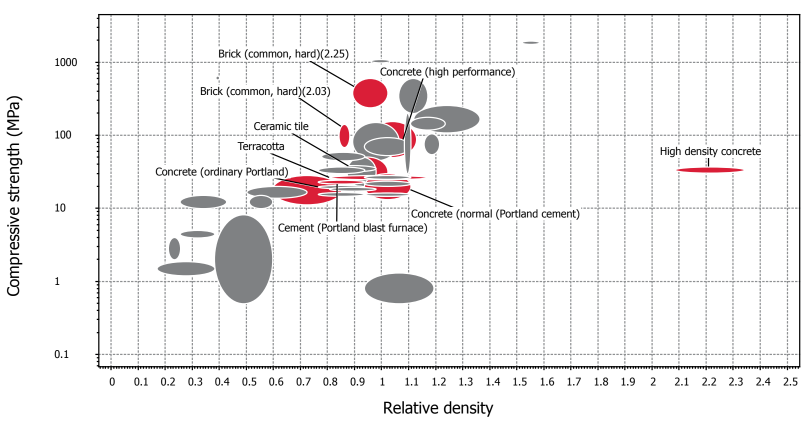


Figure 65 - Compressive strength compared to relative density (CES)

[1] *Callister, 2007, p.481*

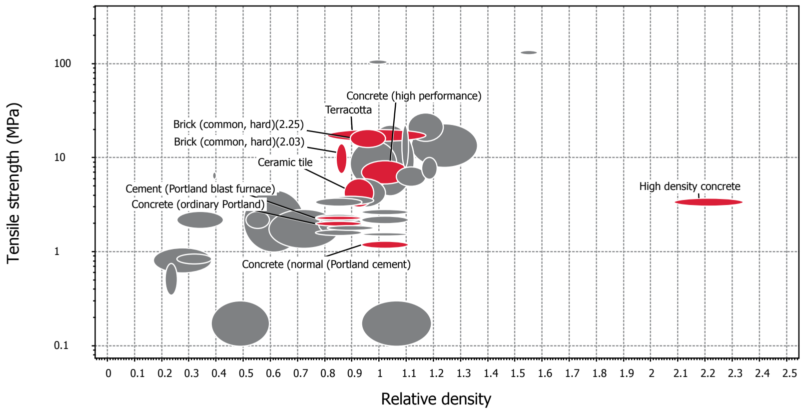


Figure 66 - Tensile strength compared to relative density (CES)

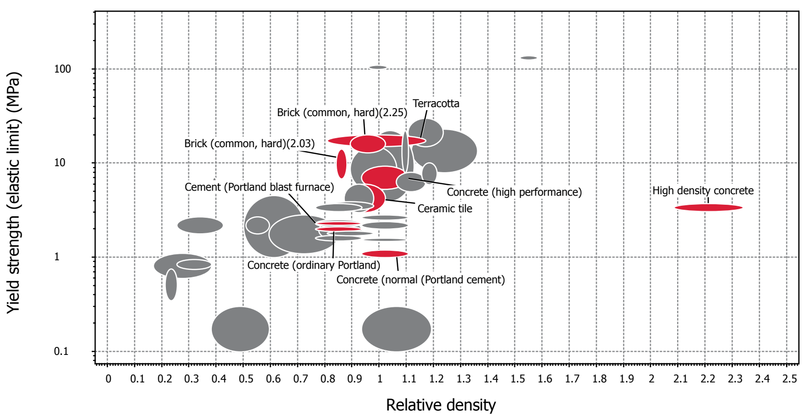


Figure 67 - Yield strength compared to relative density (CES)

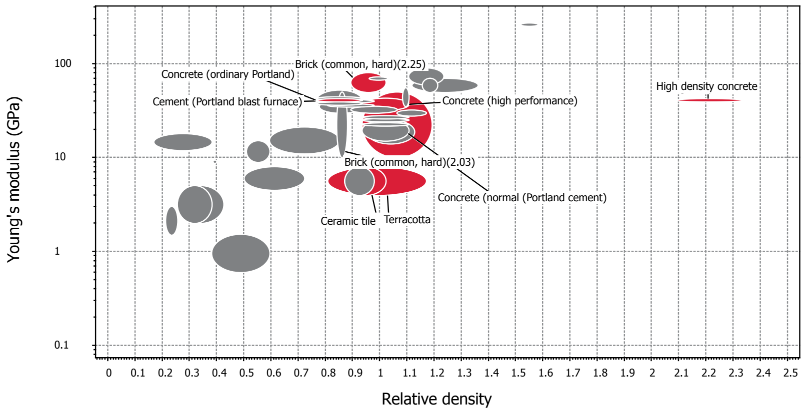


Figure 68 - Young's modulus compared to relative density (CES)

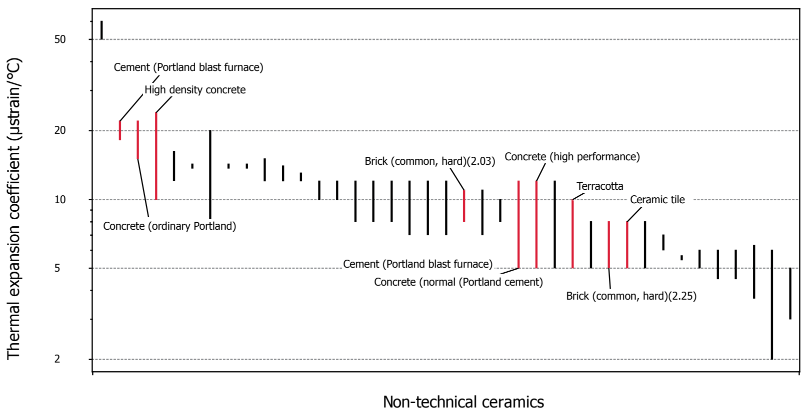


Figure 69 - Thermal expansion coefficient (CES)

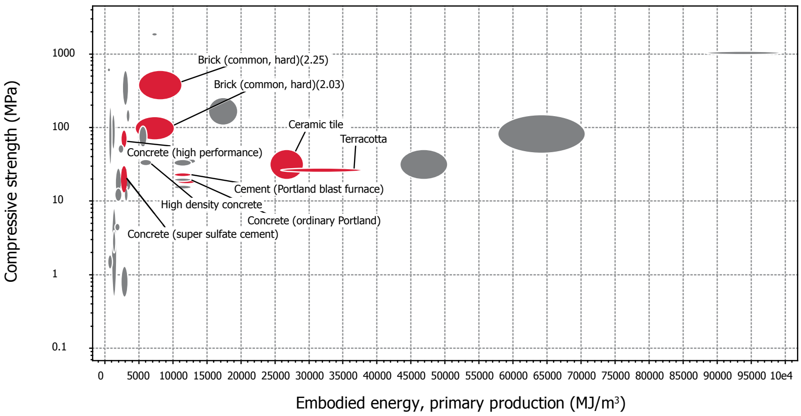


Figure 70 - Compressive strength compared to embodied energy of primary production (CES)

§ 6.1.1 *AM of Clay*

Erno Langenberg has shown the potentials of extruding a filament, drying and firing it (figure 71 and 72). In addition to this there are other concepts that can be added to process clay. The next step is to refine this method. That can be done by;

Figure 71 - 3D printed clay elements [1]

[1] Langenberg, 2014

- Increasing the resolution,
- Introducing a new production technique, or
- Combine different production techniques.

Weaving with clay filament can be used as an architectural application to produce ceramic screens and façade elements. Such screens can be used as filters and examples can be found in the Alhambra palace in Granada, where they were installed between two rooms. The challenge in weaving a screen lies in the G-code that is generated and describes the extrusion path. To extrude the filament an uninterrupted path should be used. To finish the edges of a panel the extruded corner edges can be cut off (Friedman, Kim, & Mesa, 2014, pp.262-267). Shrinkage is a problem and firing large elements will cause cracking.
New techniques could be like the MX3D printing (§3.2.5), where the clay is instantly baked after extrusion, but if multiple layers are applied on top of each other, there is a weak bounding between them.
Combined techniques are probably more suitable if an isotropic material is desired. The extra step, drying, in between raw material and the hardened state allows time for additional editing. The green ceramic body can be CNC milled before firing. In contrast to cementious materials, the chemical reaction starts during the baking and

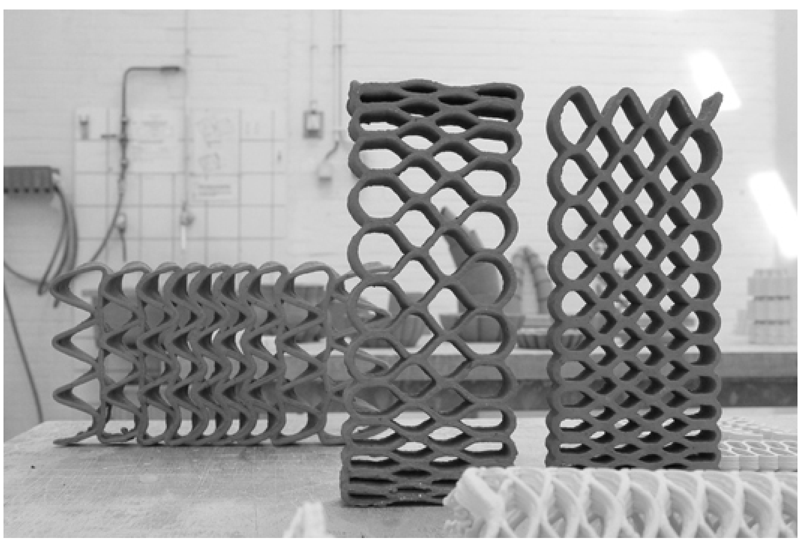


Figure 72 - 3D printed brick system [1]

[1] Langenberg, 2014

not directly after mixing. There is no waste because the dried clay that comes off during CNC can be reused. The production process would look like figure 73;

- Extruding,
- Drying (for an uniform dehumidification),
- CNC milling,

The steps Extruding, drying and CNC milling can take place several times followed by;

- Firing.

If support material is used, it should melt or burn during the firing and not react with the clay itself.

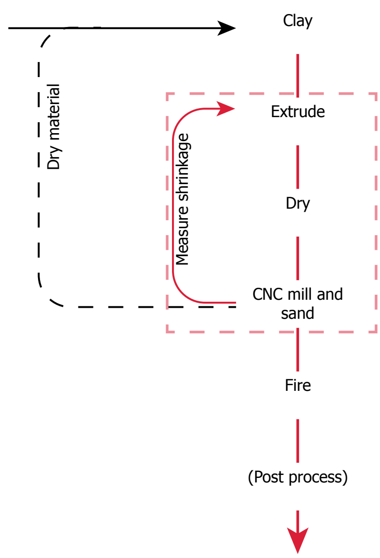


Figure 73 - Clay processing concept

§ 6.2 *Threats*

The overall quality of the AM products influences the field where the products can be used. The demand for high strength concrete will be of high importance in civil engineering and the aesthetical aspect will be less important. In architecture it is the other way around; the aesthetical part will be considered as most important. In the building technology discipline both fields come together. From here a new technology can be expanded in both directions;

- A production technique that is focused on optimised shaped and reinforced strong elements, or
- A production method that involves aesthetical freeform objects.

For the AM techniques adding additional value to a product is important. Especially since concrete is relatively cheap and waste during production do not cause high losses. The waste that is created is a larger problem concerning the environment and the LCA. Lowering the LCA is an example of added value. Next to the added value, elements that can not be made otherwise or elements that economically benefit from an AM process are interesting to be investigated. With the way threats, traditional and standardized techniques are used in mind the scheme below shows the most important advantageous and disadvantageous properties of AM in red. The

Internal origin	Strengths Geometric freedom File to factory No tooling No inventory/labour costs Sustainability Freeform design Minimum waste Testing of unique products/certification Costs per piece	Weaknesses Production time Properties of materials/anisotropy Accuracy Finishing
External origin	Opportunities Mass customization Graded materials/Micro structures Printing composites Hybrid structures	Threats Limited size/Macro scale Mass production
	Helpful	**Harmful**

Table 18 - SWOT AM [1]

[1] *Adapted from Volkers, 2010, p.18*

SWOT analysis is an economical driven prognosis. Nonetheless imitating of existing products will be done with the AM techniques during the development, to validate and compare product characteristics, but also to start from, while specific product ideas are invented. Both fields in construction industry ask for a different approach. These approaches have also different threats.
AM is a way of fabrication that is, as discussed in previous chapters, new in the field of concrete processing. Concrete processing has been automated and optimised over the last decades. Therefore it is hard to compete with existing techniques. Standardized products are not a goal of AM yet. Added value is the most promising, but such added value can also be obtained by other ways of processing concrete. Complexity in form is one parameter in the discussion what technique should be adopted as the final production process.
Using advanced production techniques for complete structures might not be the best solution. Also the fabrication of formwork / moulds are subjected to the limitations of an one phase production process like FDM. The best solution comes from combined techniques. For example, when a mould is not only made with 3D printed or CNC milled elements, but also carpentry elements are used for the simpler parts. Printing complete moulds or elements is time intensive and therefore a combination techniques can be used to produce formwork or a mould.
By using multiple techniques nearly all disadvantageous properties can be eliminated. By printed formwork the resolution determines the surface quality of the casted element. This can be compared to wood formwork that gives a certain relief. Concrete plywood or metal does not give any relief on the concrete elements, depending on the design, reliefs can easily be added in printed moulds.
Printing concrete directly skips a stage but also limits the possibilities. To print over voids with a relatively liquid material is impossible, support material is needed in the form of a support structure but a mould would be the easiest solution for this problem.
Because concrete is hard to process in with AM new developed techniques are the biggest threats and can be found in;

- Printing advanced moulds,
- Changing / adaptable mould systems, and
- CNC subtractive manufacturing.

It becomes clear that complexity in form and size are next to costs determining factors when a production method is chosen (table 18).

§ 6.2.1 *Printing advanced moulds*

Instead of an one phase AM technique, concrete can be casted in a contra form. Such a contra form can be made with help of an AM technique. The extra production step provides advantageous but also disadvantageous properties and can not be used for all kind of elements.

Advantageous properties

- Isotropic material behaviour of the concrete that is casted in the moulds, and
- Easy implementation of reinforcement.

Disadvantageous properties

- Embodied energy in the mould,
- Mould can not be reused if it needs to be broken to get the element out, and
- Single material characteristic because of casting. Gradient materials can not be casted easily.

General properties

- Production speed depends on the time needed to produce the mould.

The important characteristics of AM and printing of advanced moulds are shown in comparison to each other in the figures 74 & 75.
If moulds that cannot be re-used are printed, the customised or optimised elements are using two production cycles. The product is not optimal anymore, if the production process is taken into account, due to the use of extra labour and material. Removing the formwork stage decreases the labour and embodied energy, but the freedom of form (due to the missing support) and decreasing quality due to anisotropic behaviour of the material does occur in concrete AM processes (chapter 5).
Freedom of form is one of the differences, but a very determinative one. When Additive or Subtractive Manufacturing methods are used, the formwork's form is not important for a demoulding stage. Appendix A2 shows an ABS printed mould used to cast an freeform surface element. It can be seen that the surface quality of the mould is very important and determines the end result.
An approach to increase the performance of an advanced mould is to change the way moulds are build and used for concrete casting. For example in the jewellery industry reusable wax is used to make moulds for customized jewellery.

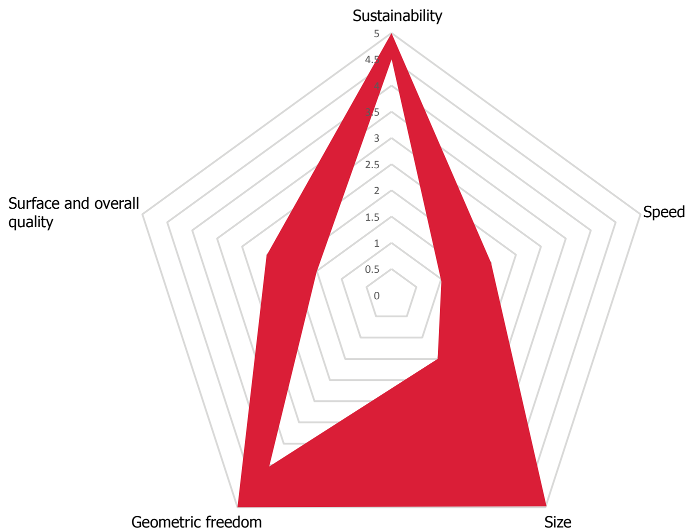


Figure 74 - Characteristics of AM of concrete

Figure 75 - Characteristics of AM of a mould

§ 6.2.2 *Changing / adaptable mould systems*

Adaptable moulds can change their form within a certain range. All standardized formwork is already an adaptable mould. By adding / removing parts, different forms can be made within the boundary of the system. In this section adaptable moulds refer to machines that can be programmed by computer. The mould can mechanically adjusted to the desired form. For the systems Adapa and Roel Schippers use a mould with a skin that can be adjusted within certain limits. It is capable of fluent forms while rugged surfaces are not possible yet with this approach. For façade elements that are fluently curved it is a good technique, but if a more complex form is desired such adaptable moulds are not sufficient anymore. Figure 77 shows the corresponding characteristics of a changing mould system

Figure 76 - Adapa mould

[1] *Adapa, 2013*

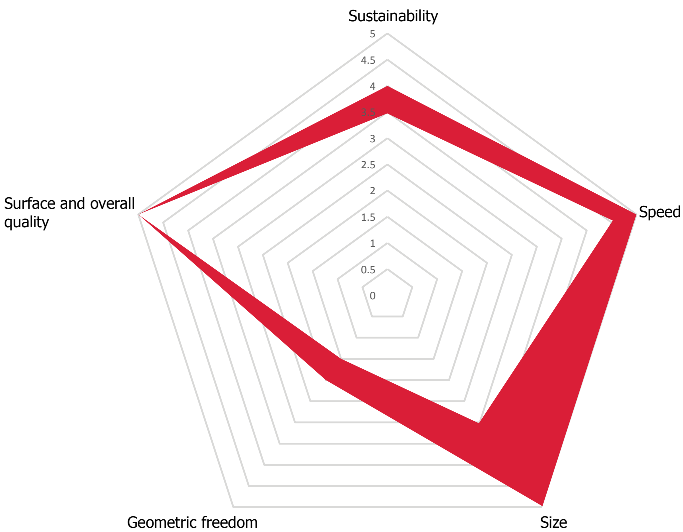


Figure 77 - Characteristics of a changing mould system

Figure 78 - Characteristics of CNC milling of concrete

§ 6.2.3 *Milling of concrete*

A Subtractive processes like milling of concrete elements has, like printing concrete and extruding layers of concrete, to deal with the inhomogeneous properties of concrete itself. The material that comes off during the milling stage, is reusable in new fresh concrete, as aggregate. When a fine mortar is used the material will be more homogeneous and the risk of parts flying of will decrease. The characteristics are shown in figure 78.

The characteristics of the threats are showed in comparison to AM in table 19. Figure 79 shows an estimation of the energy distribution of time in each process

	Additive Manufacturing	**Casting (moulds)**	**Subtractive Manufacturing**
Material use	optimised	over constructed due production limitations	optimised, but produces waste material
Formwork / mould	no	yes	no
Openings	yes	yes	yes
Hollow parts	yes	no yes with a lost formwork	no
aggregates	no (not yet)	yes	no (not recommended)
isotropic final material	no (not yet)	yes	yes
surface quality	Low Depends on resolution	Low - High Depends on formwork / mould quality	Medium - High High, depends on resolution
Freedom of form	High	Low - Medium	Medium - High
Points of attention	Quality of the stacked layers	Demoulding	Particles that fly of during CNC

Table 19 - 3 Concrete processing techniques and their characteristics

AM shows a lot of potential for freeform objects. Combined with a changeable print chamber or a process with very rapid curing elements the production time does not take considerably longer than competition. Energy consumption differs a lot with the processes. Figure 80 shows the field where AM should operate in red, without being hindered by the threats.

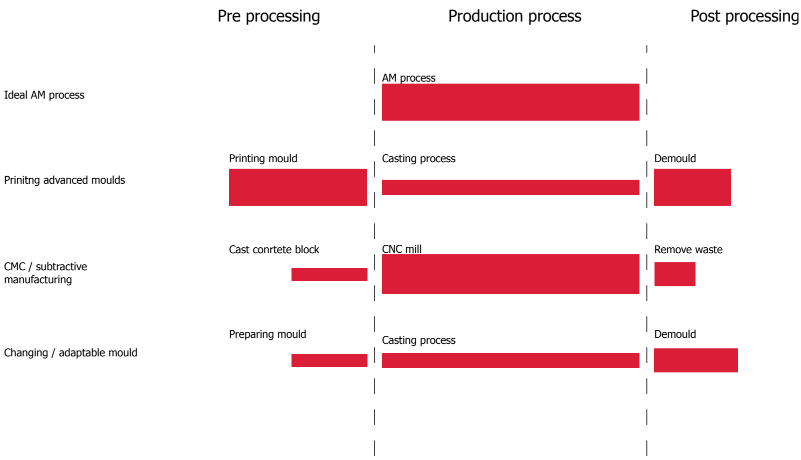


Figure 78 - Energy and time distribution during production processes

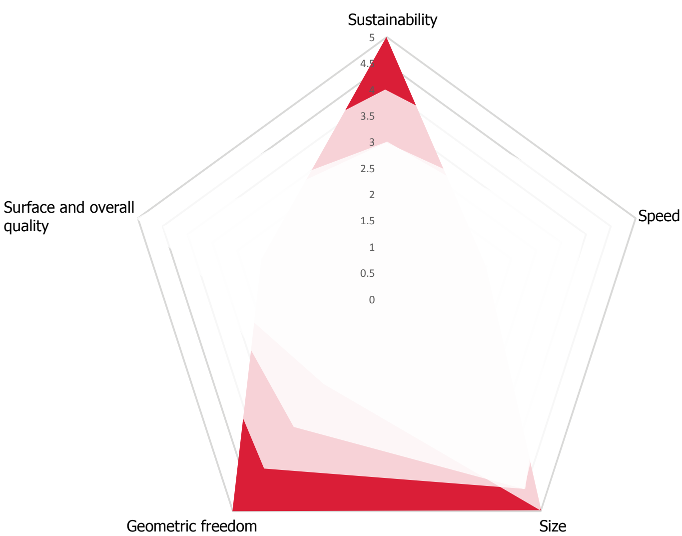


Figure 79 - Advantages of AM

§ 6.3 *Conclusion alternatives*

The main threats for AM of concrete can be found in more traditional processing techniques that are supported by AM. For example the AM of the formwork. The traditional, over the centuries evolved, way of casting concrete gives an isotropic material. It can be reinforced and the surface quality is determined by the surface quality of the formwork / mould. The production of series can be easily achieved, if the element's form allows formwork that can be removed in one piece (or a few pieces). The production time depends on the time to cast and cure in the formwork. In case of AM of the concrete element the production speed is depending on the AM technique and the corresponding speed of this technique. The way it is supported also has its influence. If the element is supported locally and can be removed from the 'print chamber' other elements can be printed directly afterwards. If the element remains in the chamber to cure this has a high impact on the overall production speed. The threats can be minimised if AM provides the technique that can produce products with an added value. This is the part of concrete processing where AM should be used. The part that other techniques can not provide for (figure 79).

Concrete itself is a challenging material to process using an AM production technique. The chemical reaction taking place in this composite material leaves a lot of opportunities for competitive ceramic materials that have comparable performance regarding the Young's modulus and compressive strength. Clay has the advantage that it can be formed without the interference of a chemical reaction. The chemical reaction happens during firing after the form has been defined. Unfortunately cracks from baking can, like poor compacting does to concrete, influence the performance of an element in a negative way. Especially large elements are vulnerable to cracking during firing.

Both, the threats and the alternative materials, are based on the workability of concrete in an AM process. Clay simply dries after extrusion and the materials that are used to print the formwork, use a relatively easy phase change or adhesive to apply the layers on top of each other. This shows again, that as mentioned before, that the AM process should not be dictated to a material, but hat the AM process should be developed around the material characteristics in the broadest sense of the word.

II Design

7 Roadmap (printer concepts)

After evaluating the existing techniques in the previous chapter, new designs and processes that improve the processing of concrete are the focus of this chapter. A small summary and the context of the desired way of designing leads to the roadmap. The roadmap is the outcome of the research combined with the visions on how the concrete AM technique has to evolve in order to use it in a beneficial way.

§ 7.1 *Design methods*

Before new production techniques can be elaborated on, the design methods and desired characteristics of the designed object need to be known. For the design of AM (concrete) products nature can be a large inspiration. Humans and trees have optimised load bearing structures. The human skeleton has evolved over thousands of years. Our bones are not solid but the internal structure consists of strands that stabilize our bones (figure 80). Nature optimises more structures. Trees are a great example. The loads that they have to deal with are distributed in an efficient way. They have the ability to adapt to their environment.
This adaptability is illustrated by a tree that was placed against a handrail. The tree uses a part of the rail to distribute his load. The bottom part of the trees trunk is significantly thinner than the part that is on top of the rail. Figure 81 shows a schematic force flow.
With this in mind optimised structures can be designed. However production technologies are behind if compared to design methods and possibilities. Contour crafting and 3D-Concrete printing extrude elements with simpler geometry. D-shape, however it is not concrete, is able to 3D-print relative complex forms.

To design optimised elements with a Soft Kill Option (SKO) and Computer Aided Optimisation software (CAO) to calculate the needed material and the location can be used. CAO adds and removes material to spread the load on the component. SKO takes design limits into account and it removes the not load bearing parts. The result is an element with reduced weight but with the same performance (Mattheck, 1998, p.261). The next step in an optimising process is to implement internal voids within the structure. By increasing the diameter of the structural cores the moment of inertia increases due to the location of the materials used. The voids within can be used to implement services. Eventually software will determine the result based on the used

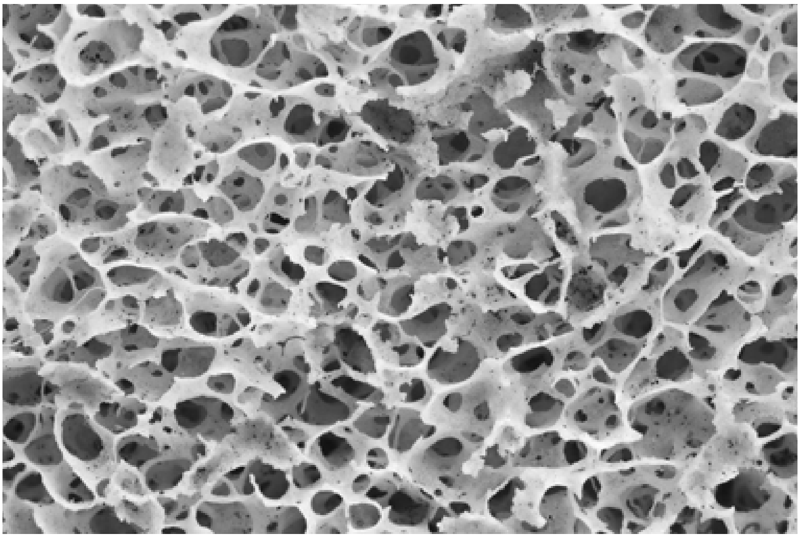


Figure 80 - Human hip bone texture (1)

parameters. There is, regarding material use, an optimum. This can be calculated on the base of parameters used in a parametric design program like Grasshopper.

§ 7.1.1 *Parametric design method*

Due to the parametric design it is possible to generate designs by changing the input parameters. In the design of for example a façade cladding characteristics like ventilation, sound absorption and heat exchanging can be integrated.

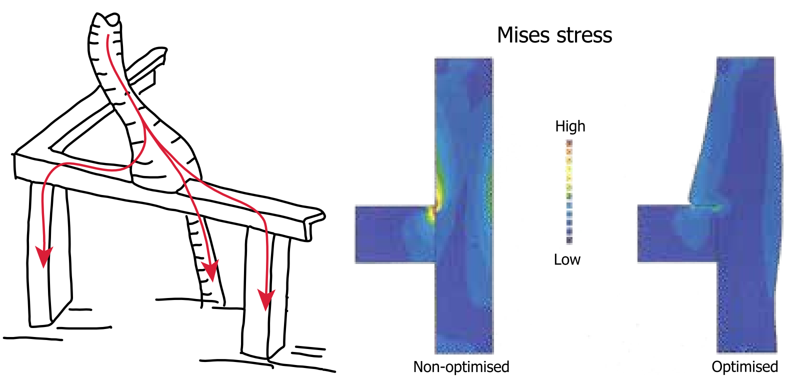


Figure 81 - Tree-Stone Friendship (2)

[1] Siemer, P., 2008
[2] Mattheck, C.,1998, pp. 96-97

If the points of fixation are fixated in a model, the Galápagos function in Grasshopper can be used to optimise the geometric shape within the indicated parameters. These models can be send to automated production processes. The interface for the future vision techniques and the model needs to be made, but that is the field of computer technology.

§ 7.2 *Evolved and new techniques for concrete AM*

The characteristics of concrete differ from most materials used for AM. The chemical reaction and being a composite are of great importance in discussing the possibilities of AM for concrete (table 21).

Mechanism	**Constituent material**	**Composite**
Phase change	Steel Plastics	
Drying	Clay	
Chemical bonding	Gypsum	
Instant chemical reaction	Cement	Concrete
		Smart materials

Table 20 - AM material properties

In the future vision, the characteristics of concrete will be adapted to the production technique and vice versa. Concrete mixtures come in a lot of different varieties as shown in figure 9. The Aggregate size determines the name and category, but next to the composition and strength, workability and green strength can differ within each category. For example, a high strength concrete with a high green strength can either be normal concrete but also an UHPC.

Because either the material or the production technique has to be adapted to create an satisfying result. The desired characteristics of the material are showed by "Zappie" in table 21. Table 22 shows which characteristics a process should have to process concrete that is commonly used.

The AM processes used for plastics are also opimised for the materials used. The mechanisms behind the curing are most of the times simpler (table 20). Elaborating the future visions into a concept printer, thus requires also a concrete expert to take care of the right mixture.

Since technology is not able to print high quality massive elements, optimised elements are even more challenging. To evolve the techniques to make that possible a future vision is needed. The roadmap shows these visions. To obtain the dedsired characteristics the production methods like Contour Crafting and 3D-Concrete printing function as a basis to evolve the concrete AM techniques. New ways of processing can be divided in four main groups;

- Evolve existing techniques,
    - Combine Contour Crafting and Concrete Printing,
    - Improve D-Shape,
- Hybrid techniques. To make use of the advantages of both techniques,
    - 'CNC mill/form' the surface before/during hardening after it has been 3D printed or extruded,
    - Print/extrude in a substance that partly supports the structure and takes a part of the 'gravity', like NSTRMNT §3.2.5.,

			Desired material
	AM process like FDM	**AM process like 3DP/ Polyjet**	**"Zappie" (new material)**
Form of element and smoothness	- Resolution determine surface quality - Viscosity determines the scale of a cantilever	- Resolution determine surface quality - Viscosity determines the amount of support material	- Self smoothing - Easy to shape - High viscosity
Product	Layered material	Layered material	Becomes uniform
Composition	- Reinforcement between layers is hard - Extruding and distribute aggregates is impossible	- Reinforcement needs to be printed(welded) -Print aggregates themselves makes no sense	- No reinforcement needed or fibres - Reinforcement is also between layers
Strengths	Differs	Differs	High strength
Difference in strength perpendicular to workspace	- Bonding between the layers due fixation of new layer on old layer	- Bonding between the layers due fixation of new layer on old layer	Isotropic material - Interlayer bounding
Curing	Has to cure before weight of additional layer can be handled	Has to cure before weight of additional layer can be handled	Fast curing
Treatment	- Easy to extrude - Fast curing before next layer	- Easy to apply - Fast curing before next layer	- Easy to extrude - Self compacting
Viscosity	Green strength	Green strength	Green strength (less hardening needed)
Additional parameters	No formwork	Support material where needed	Processable without formwork

Table 21 - AM desired material properties

- A nozzle that acts as support for the first seconds or activates an increased reaction speed by use of heat or a gas as a catalyst. (MXRD §3.2.5),
- A dissolving lost mould inside an element to embed voids within the AM element without reducing speed because of the need of an increased resolution.

- Implement new techniques in old processing techniques, and
- New ideas

The threats of manufacturing a mould with an additive and subtractive technique can be implemented in evolved AM techniques or used to support old processing techniques with AM implementation.

Implementation of parts that are missing nowadays;

- Print with larger aggregates instead of mortars,
- Print different material compositions (gradient materials),
- Larger reinforcement between the layers of the element, and
- An uniform element with reinforcement aggregates and the same consistency.

The roadmap on the next page shows the existing and new concepts with their main features. The feasibility of implementing the new features is described in the next section.

			Desired production types with existing materials
	Concrete	**UHPC**	**New technique printing**
Form of element and smoothness	Surface quality determined by mould	Surface quality determined by mould	High resolution Mechanical smoothing
Material	Uniform	Uniform	Isotropic material or controlled anisotropy
Composition	- Reinforcement bars or fibres - Aggregates	No reinforcement needed - Aggregates <2mm	Capable of reinforcing
Strengths	All strengths	High strength	Capable of high strengths
Difference in strength perpendicular to workspace	Isotropic material	Isotropic material	Bond and compacts like normal casted concrete
Curing	Dries at once in a 'slow' curing process	Dries at once in a 'slow' curing process	Depends on technique
Treatment	Compacting needed	Can be self compacting	Depends on technique
Viscosity	Differs	Liquid	Green strength not necessary
Additional parameters	Formwork needed	Formwork needed	No or little formwork needed

Table 22 - AM desired production properties

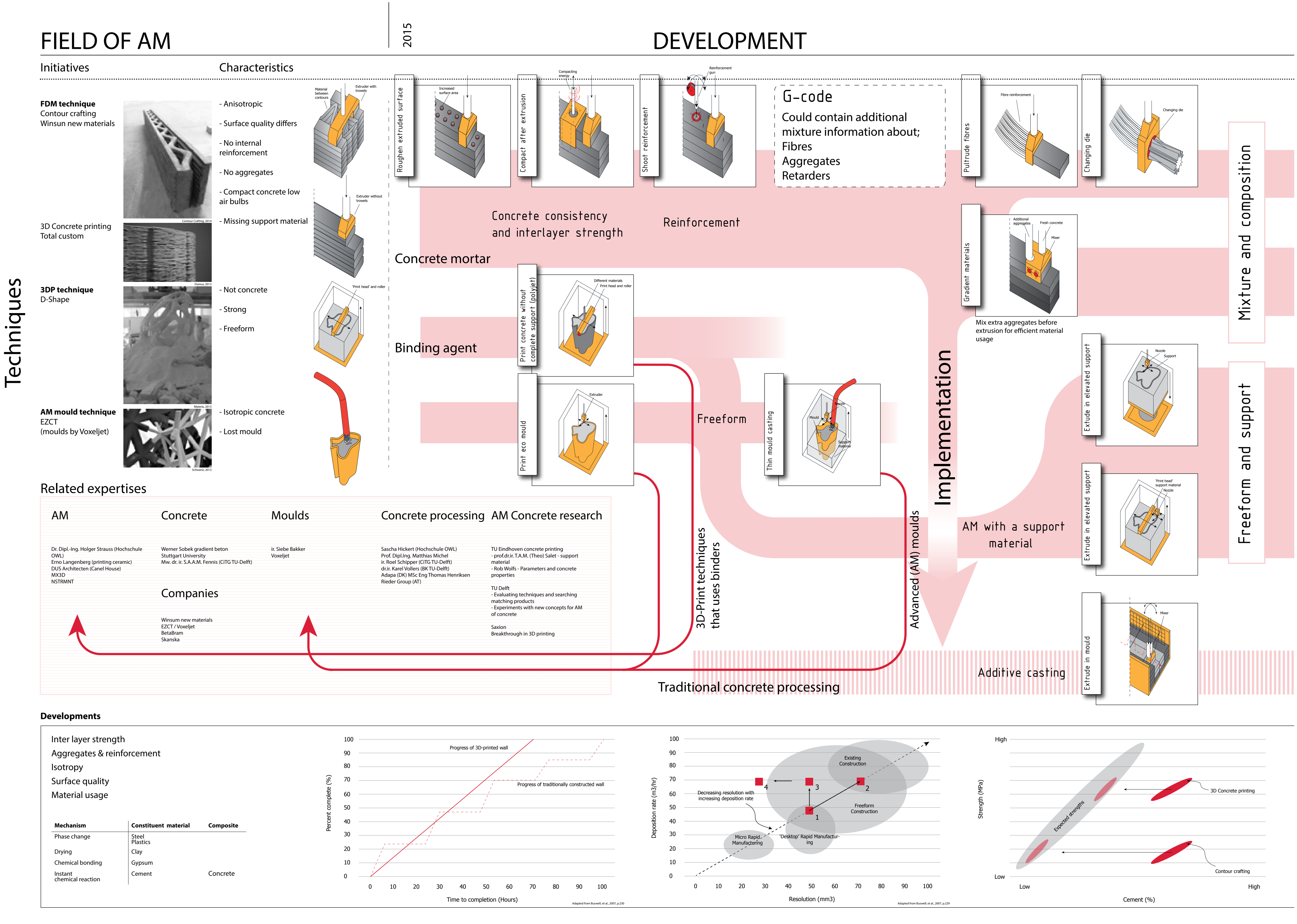


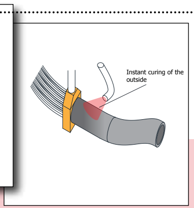
Figure 82 - Roadmap

CONCLUSION: FUTURE VISION

Hybrid techniques description

Pultrusion

Instant dry extrusion

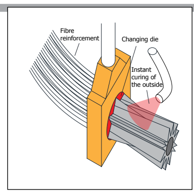


Combining extrusion and curing

Instant dry extrusion/pultrusion

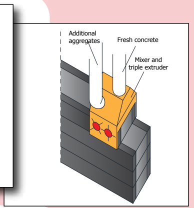
High furface quality elements with reinforcement that do not need to be finished.

e.g using a non newtonian fluid



Extrusion

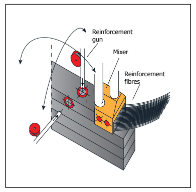
Multiple mixture extruder



The multiple mixture extruder mixus to obtain the characteristics that optimise the mixture and material composition

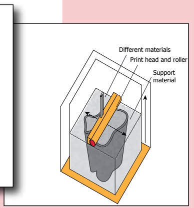
Orientated fibre reinforced concrete

The extrusion head is used to mix, extrude and reinforce. Reinforcement is used for inter layer strength and for load distribution.



Resolution
Curing

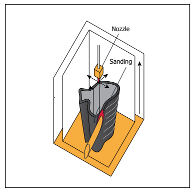
Polyjet concrete extrusion



Polyjet in combination with elevated support printing increases the resolution

Print mill sand

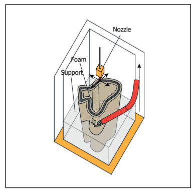
Print with a low resolution the desired form and use milling (or lasers) as subtractive technique to finish the element.



(Mixed extrusion with) elevated support printing

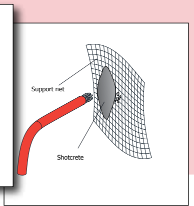
Use a (advanced) extrusion head to print a layer and add / cover the area around with loose support material after the extruded layer has been covered with a protection layer. The process is repeated till the element is finished.

The protection layer prevents dehydration of the concrete



Shotcrete

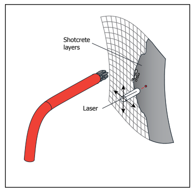
Reinforcement shotcrete



Shotcrete is used to cover the reinforcement with layers of concrete

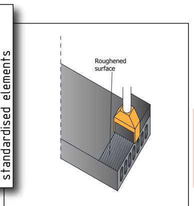
Support net spraying

Print or weld a support frame that can be used as reinforcement and to define the geometry of the AM element. It is the method that builds a layer around a core. The net is covered with concrete using spray on.



Customise

On site customising of standardised elements



Standardized elements can be customised on site when the surface binding is strong enough by e.g. roughening it mechanically

Characteristics & Evaluation

Fast
Reinforced
Can be automated easily
High quality concrete (extruded at once)

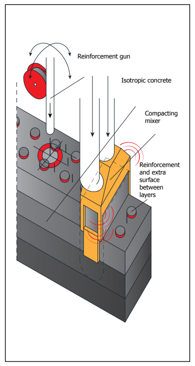
Orientated reinforcement
Controlled material composition
Less free form
More isotropic
Less material

High surface quality
Less resolution needed
Faster printing process
Faster overall process

Minimising printing time
Efficient support
Freeform
Controlled material composition

Build around the reinforcement
Freeform
Fast process
High surface quality due post processing

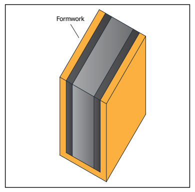
Advanced extruder



Aligned fibres
Controlled mixture
Inter layer strength
Smooth surface

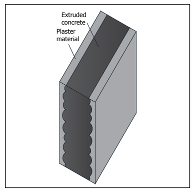
Advanced extruded elements with different densities are extruded at once due to multiple extrusion points in the die. The extruder head can be used for different process approaches

PRODUCTS



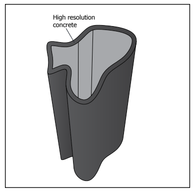
Gradient material

Large structural elements with different distribution of aggregates and composition. With or without formwork.



Core parts

Print in low resolution, to increase production speed. These elements will be covered or finished afterwards.

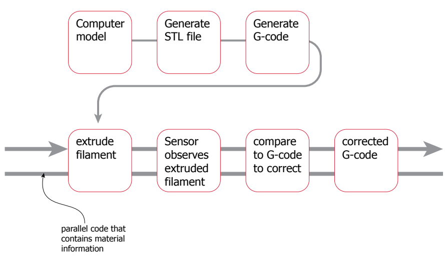


Freeform

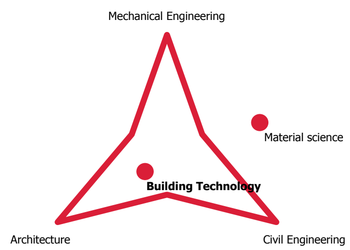
Freeform, high resolution elements,
Joints of standarized systems, and
3D refurbishment elements

ROADMAP: **future vision**

G-code



Interdisciplinarity



CONCRETE IN AN AM PROCESS

Freeform concrete processing

This report examines the additive manufacturing (AM) of concrete, its possibilities, feasibility and advantages over existing techniques. Traditional processing techniques are adapted to the characteristics of concrete and concrete does not let itself dictate how to behave. The possibilities for products made with an additive process are endless, but just replacing existing production methods with additive ones is still impossible. Although improved freeform production techniques are the aim of this research, this does not mean that more freedom in form is by definition the largest improvement that AM can offer at the moment. From another point of view the implementation of additional functions in traditional products can be of great value.

A roadmap envisions how the technique has to evolve in order to implement the characteristic properties of concrete. Product ideas and an evaluation of the techniques shown in the roadmap are related to the developments to achieve an increase in speed, surface quality and strength in the AM production technique, next to the requirements that have to be set regarding a matching fresh concrete mixture.

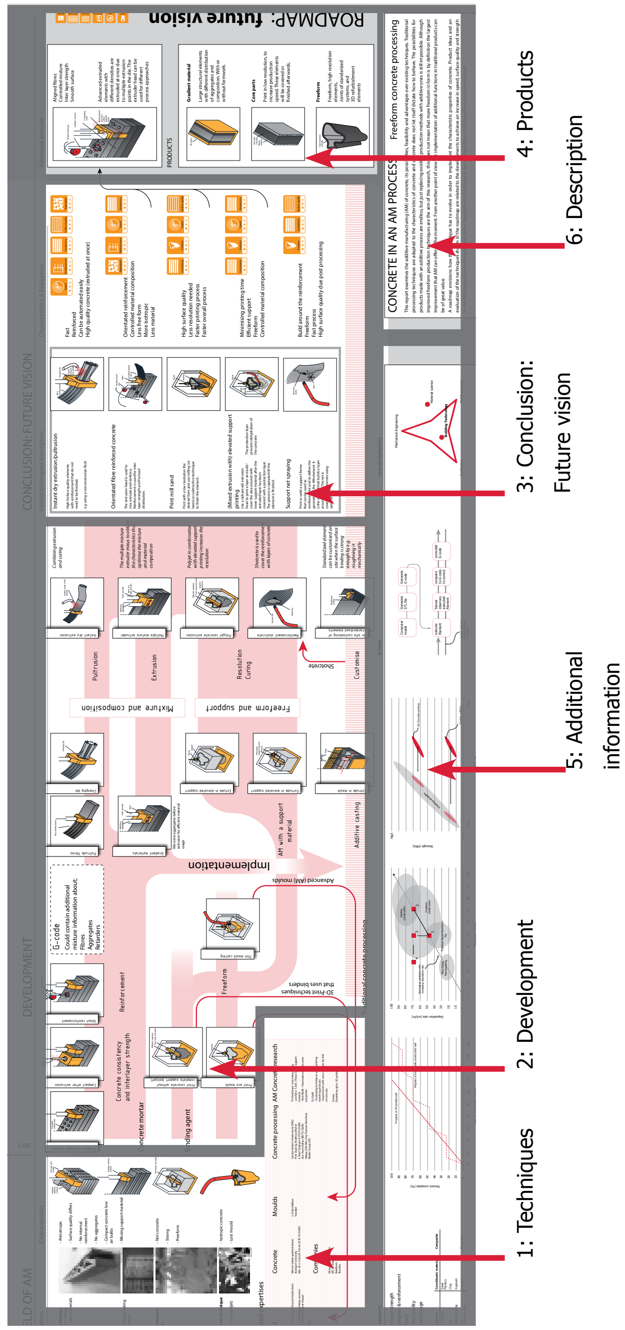


Figure 83 - Roadmap

§ 7.3 *Vision on AM of concrete*

The roadmap is divided in 6 sections;

1 Techniques
2 Development
3 Conclusion: Future vision
4 Products
5 Preconditions
6 Description

Part 1 is a summary of the existing techniques described in chapter 5. Part 5 shows information about the current techniques, preconditions and explains the motivation behind the development and future visions with their resulting products. The requirements that are set for a successful production technique are discussed in this report. Part 6 shows a general description to clarify the future visions in context of the report's conclusions summarised in the roadmap.

§ 7.4 *Development*

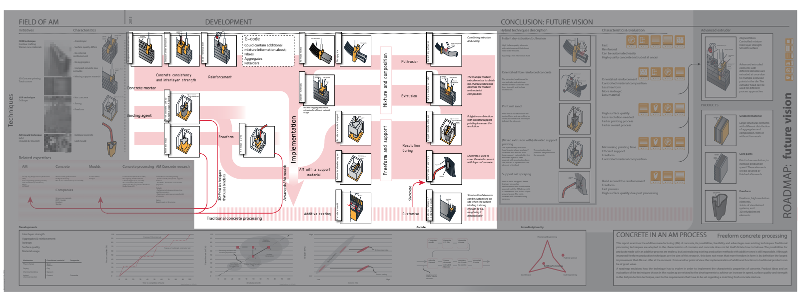


Figure 84 - Roadmap: developments

The development is a process that takes place right now. Patents are requested by the other initiatives, Which is the cause of that no publications with results are available yet. General issues that can logically addressed to the development are;

- The surface quality,
- The inter layer strength,
- The absence of reinforcement,
- The position of the materials within the composition formed from filament,
- The manufacturing speed, and

- The freedom in form.

To overcome these challenging shortcomings the roadmap shows improvements for them are showed in part 2 of the roadmap.

§ 7.4.1 *Development in extrusion techniques*

Techniques that look like FDM can be optimised by increasing the inter layer strength. This can be done in several ways;

- Roughen the extruded surface by extruding a surface like a mogul piste. The increased surface area with the added z direction creates a stronger connection between the layers.
- Compact the layers after extrusion. Till a certain moment concrete can be compacted. If those time intervals are regulated this can help to mix the layers together, and
- Mechanically connect the layers by shooting reinforcement through the extruded of concrete.

By shooting reinforcement into the concrete, UHPC with controlled fibre alignment, can be achieved. The fibres along the direction of extrusion cannot be embedded. To embed the fibres with an extrusion process can be solved by embedding them along the extrusion path.

In addition to the controlled positioning of fibres, an AM technique, in comparison to standard casting, allows to adjust the mixtures density in real time. To make lightweight porous concrete the extruder can mix additional granulates like expanded glass balls or a chemical raising agent to the mixture just before it is extruded.

The G-code, normally used to describe the extruder's path, can be linked to the desired material properties and other parameters (§7.8). Those developments can be accommodated and combined in an "advanced extruder head". If the fresh concrete mixture is too wet, using different mixtures with densities that differ, could start to float on each other. The experiments in Appendix A8 shows the outcome of processing mixtures with different densities.

A side track of the pultrusion is a die that can change its form. This allows to extrude line-like elements with reinforcement and a changing section along its path. Rapid curing can be embedded in such an extrusion process because no inter layer strength is needed and the aggregates are equally distributed over the object. In the end these techniques can also be combined, but experiments have to be done to evaluate which combinations work best.

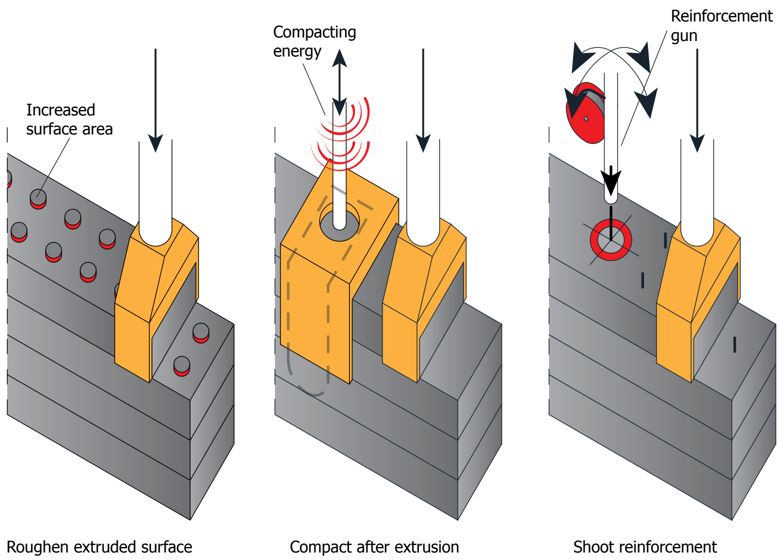


Figure 85 - Techniques to increase inter layer strength

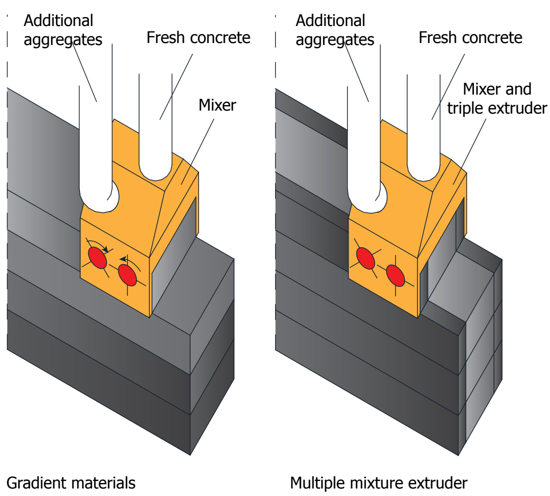


Figure 86 - Extrusion of different materials each layer or at once

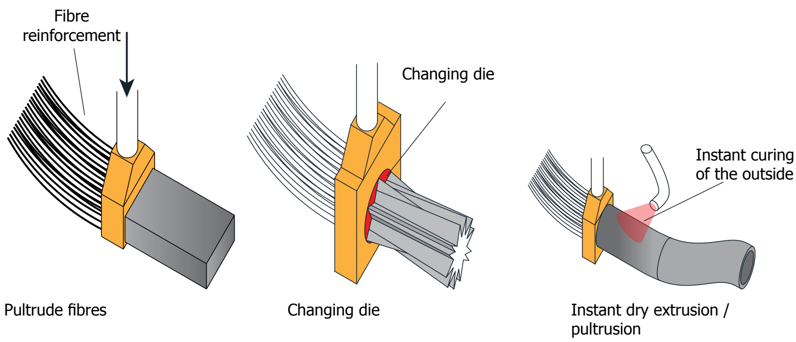
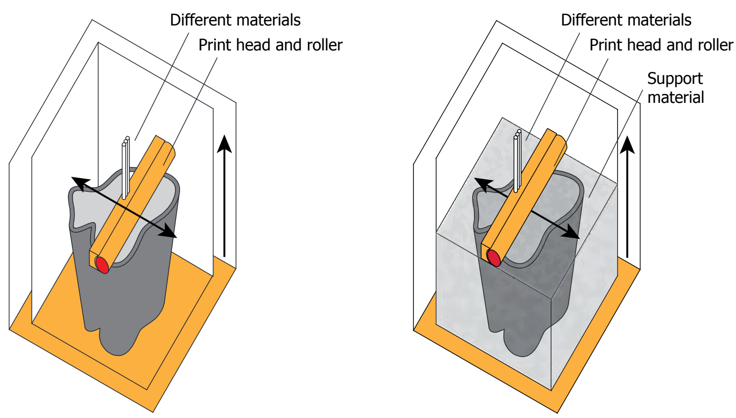


Figure 87 - Reinforced extrusion techniques

§ 7.4.2 *Developments in 3D-printing techniques*

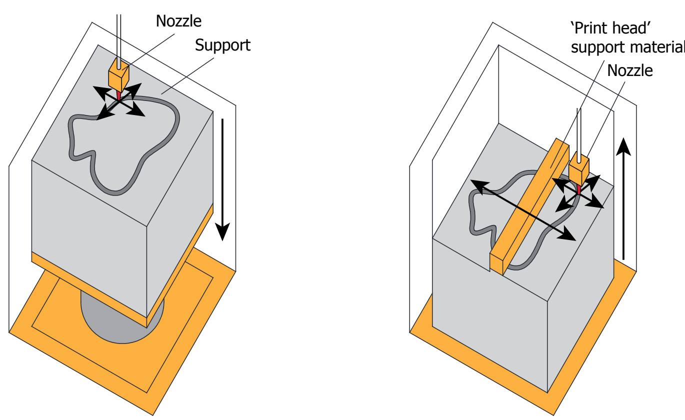
3D-printing techniques like D-Shape are time intensive, since all layers have to be built separately, but it has the advantage of incorporated support material. To develop this process it should become more like a Polyjet technique, a multi-material technique without a binder, that uses concrete instead of powder and not a separate binding agent. Polyjet allows to extrude only where the material is needed. Multiple materials can be extruded at once, allowing to make (temporary) support structures where needed. Another approach and development will be the elevated support technique. This technique consists of printing or extruding a single layer of material where after in the print chamber liquid / granular material is added to support the path. This process repeats till the element is finished. Advantageous characteristics are the decreased speed of adding support material and the ability to recycle the support material. The elevated support method can take place on a platform that is lowered. The support material will fill the outside of the chamber automatically, but not the inside of the printed object. Print from the floor of the chamber is the second option that avoids the need of a moving platform, which will be hard with in size increasing elements. In this case the support needs to be selectively sprayed on top of the existing layers, to prevent voids from being filled.



Print concrete without complete support (polyjet / 3D-printing)

Polyjet concrete extrusion with elevated extrusion

Figure 88 - PolyJet like techniques



Extrude in elevated support with moving platform

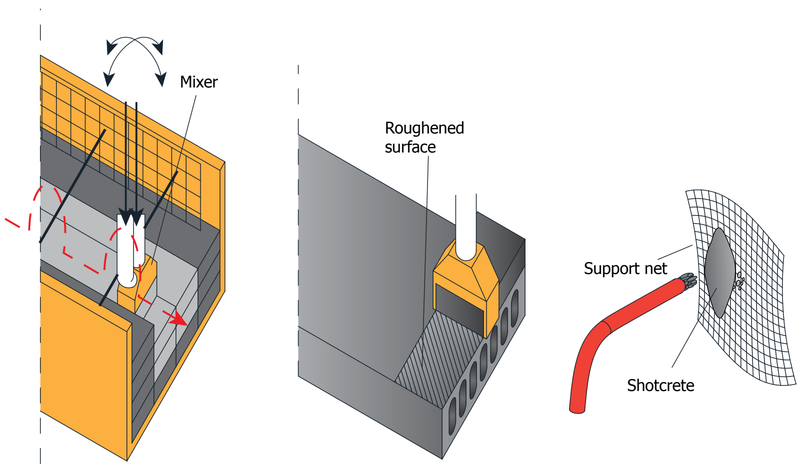
Extrude in elevated support

Figure 89 - Elevated support printing using an extrusion nozzle

§ 7.4.3 *Implementation in traditional concrete processing*

An advanced extruder (§7.6) which can mix the material instantly can be used in the traditional concrete processing processes. It allows to additive cast in formwork. This reduces environmental impact due to optimisation in material usage. Additionally, standardized elements can be customized. Roughen the surface of a standardised product in such a way that additional applied concrete will bind to the element to customise it by adding additional layers of concrete.

Although shotcrete is used to cover the walls of a tunnel, it can also be used to make a freeform element. Spraying layers of concrete on a reinforcement net will allow to additive manufacture a freeform object. The reinforcement wire mesh acting as net can be made using different technique including AM.



Extrude in mould

On site customizing of standardized elements

Reinforcement shotcrete

Figure 90 - AM techniques implemented in traditional concrete processing processes

§ 7.5 *AM Techniques: Future vision*

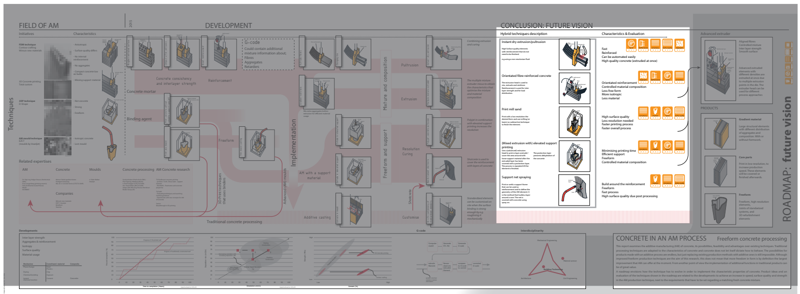


Figure 91 - Roadmap: future vision

The future vision is a mixture of the developed improvements and new technical inventions. Also traditional concrete methods have been implemented in the AM future visions. The visions can be split in three different approaches:

- Extrusion/pultrusion,
- 3D-printing, and
- Building layers around a core.

These categories are based on their development trajectory. The other way around with the implementation of AM in the existing concrete processing is shown in the development part. Extrude different and regulated concrete mixtures in a traditional casting process (extrude in formwork).

The five visions with the highest potential for concrete processing are;

- Elevated support printing,
- Reinforcement / support net spraying,
- Print mill sand / lasercut,
- Instant curing extrusion / pultrusion, and
- Fibre orientated reinforced UHPC

The development is performed by the competition as well. Its important to obtain a leading role in the AM of concrete. The visions showed are one step ahead of the competition. The new concepts are of great importance since, although it cannot be verified, the pending patents from Contour crafting, 3D-concrete printing, D-Shape will concern optimising their processes, and not about a complete change in their concept. The future visions are a result of the analysis of existing techniques, the alternatives and threats for AM of concrete and from an innovative point of view.

Techniques

Category	Name	Description	Comparable existing techniques involved
Additive	Contour Crafting	Concrete filament is extruded on top of each other. (§5.3.1)	
Additive	Concrete Printing	Concrete filament is extruded on top of each other. (§5.3.2)	
Additive	D-Shape	3D-printing process that uses powder and a binder (§5.3.3)	
Additive	Instant curing extrusion	Using a nozzle that cures the outside of the heat/ temporary support, Change the diameter of the nozzle, allows to extrude a changing form.	MX3D
Additive	Fibre orientated reinforced concrete	Using an extrusion process and additional machines to extrude and shoot fibres in the concrete.	Next generation extrusion
Mixed	Print mill sand	Finish the AM rough printed concrete by cnc milling the surface	Milling the complete form
Additive	Elevated support printing	Extrude a layer of concrete. The layer will be supported by granular materials that can be reused and are added during printing	D-Shape
Mixed	Support net layer spraying	Print or produce reinforcement nets that are used to apply layers of shotcrete on.	-

Table 23 - new AM concepts comparison

Speed	Aggregates	Reinforcement	Mix different material compositions	Material isotropy	Internal voids dissolving material etc	Surface quality
High	No	Yes, fibres	Maybe	Layered	Yes	Medium
High	No	Yes, fibres	Maybe	Layered	Yes	Low
Medium	No	No	Yes the layer composition	No	No	Medium
High	Yes	Yes, fibres	Maybe	Material behaves / cures different in the core	No	High
Medium	Yes	Yes, orientation controlled fibres	Yes	Isotropic, but can be manipulated	No	Medium, depends on resolution
Medium	Yes, but not at the surface	Yes, fibres	Maybe	Isotropic	Yes	High, but aggregates can spring of
Medium-High, depending on the resolution used	Yes	Yes, fibres	Yes, if the extrusion head can mix	Isotropic Inter layer bounding is important	Yes, but they need to be fixed in the concrete, because otherwise support material fills the voids	Depends on resolution
Medium-High, depending on the (AM) technique used for the net	Yes	Yes	Yes	Isotropic	No, but hollow elements can be attached to the net	Medium, depends on post processing as well

§ 7.5.1 *Instant curing extrusion*

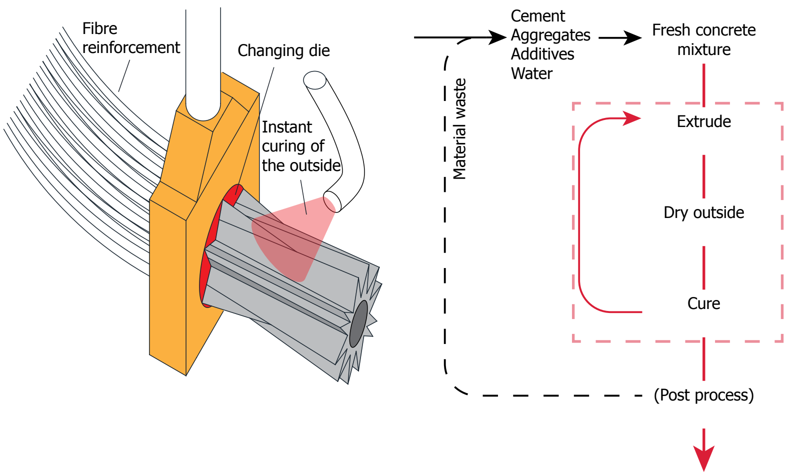


Figure 91 - Instant curing extrusion / pultrusion

Concrete hardens due to a chemical reaction. By changing the composition and by adding extra blowers to the extrusion head, the concrete can be cured on the outside instantly. There is no support needed anymore after extrusion and the line-like elements becomes formwork for the core of the element. Attention needs to be paid to the internal stress. The main advantage is that the element is extruded at once. Because the die changes its form it is a continues process without layers. The extruded concrete is isotropic and can contain larger aggregates.

Advantageous properties:

- Reinforced,
- Fast,
- Can be automated easily, and
- High quality concrete (extruded at once).

Disadvantageous properties;

- Cracking due to internal stress concentrations.

§ 7.5.2 *Fibre orientated reinforced concrete*

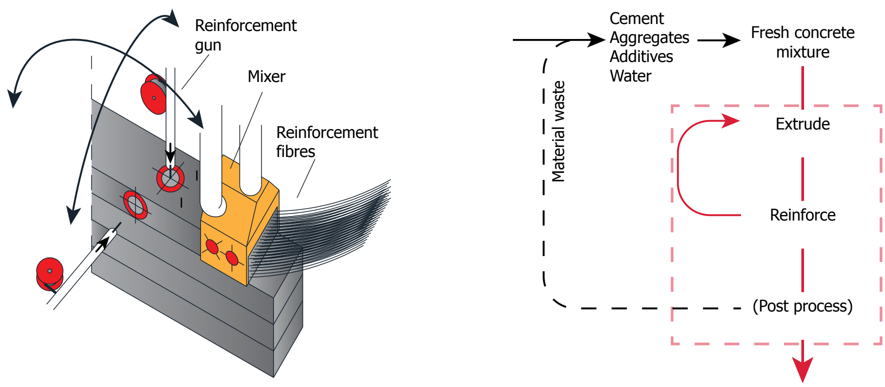


Figure 92 - Fibre orientated reinforced concrete extrusion

Orientating the fibres in concrete has great potential. The fibres used nowadays are randomly spread across such a fibre reinforced mixture. Therefore the needle like reinforcement is everywhere instead of concentrated on the desired spots and in the desired direction. In AM it can fulfil, in addition to the improved location controllability, the function to generate the desired inter layer strength.

<u>Advantageous properties:</u>

- Minimising printing time
- Efficient support
- Freeform

<u>Disadvantageous properties;</u>

- Resolution determines surface quality

Figure 93 shows an example of fibre reinforced concrete. The fibres are concentrated in the lower part of the element.

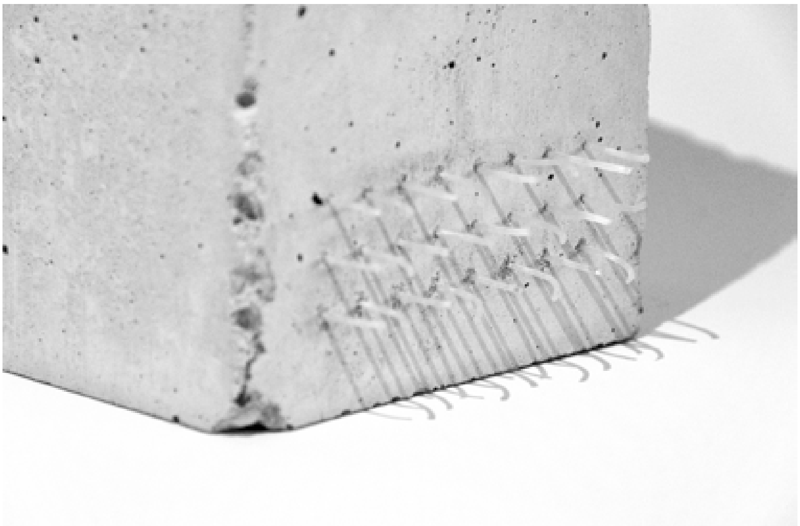


Figure 93 - Fibre reinforced concrete

§ 7.5.3 *Print mill sand*

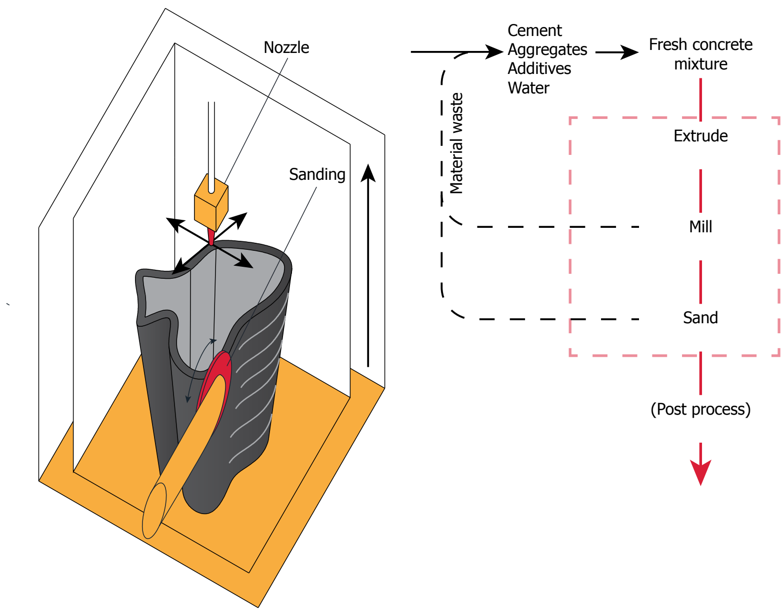


Figure 94 - Print mill sand

Subtractive manufacturing is the opposite of AM, but a combination of the two methods leads to processes like print mill sand. First the geometry is printed quickly in a low resolution, after curing the material will be removed by use of a subtractive process. The surface quality can now be controlled by the subtractive process, for which traditional milling tools or a laser can be used. Large aggregates have to be avoided at the surface, since these can spring of and damage the surface.

<u>Advantageous properties:</u>

Better surface quality

Less resolution needed

Faster printing process

Faster overall process

<u>Disadvantageous properties;</u>

- Waste during milling

§ 7.5.4 *Elevated support printing*

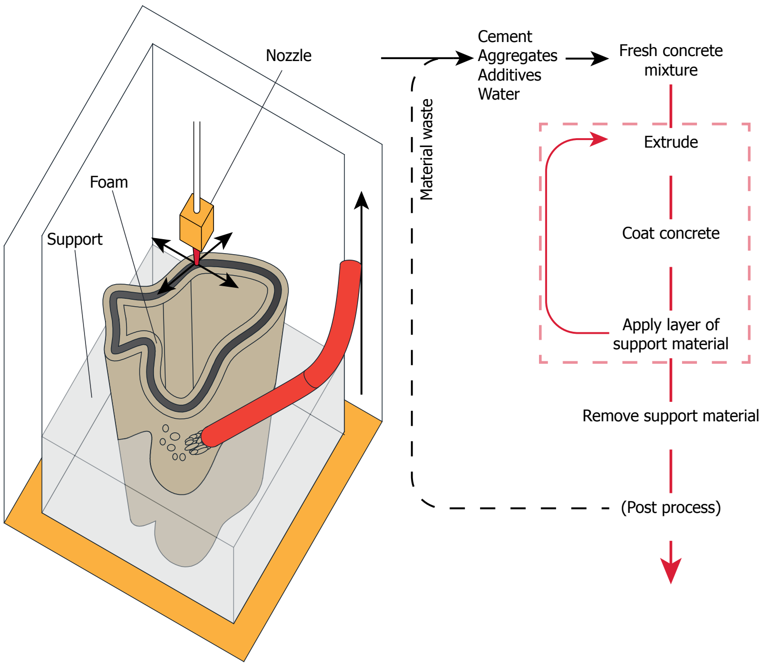


Figure 95 - Elevated support printing

Elevated support printing can be even more advanced than described in the developments. To prevent dehydration of the concrete a layer of, for example biodegradable foam, will be applied after extrusion. This has to be done just before the next layer of support material will be selectively sprayed around the extruded layer of the element. This also prevents that the support material sticks to the element (figure 97).

This technique combines FDM and 3DP. The extrusion head's functions can be as advanced as desired, because the elevated support does not affect the extruder.

<u>Advantageous properties:</u>

- Minimising printing time
- Efficient support
- Freeform
- Freedom in material composition

Disadvantageous properties;

- Print chamber is needed

Figure 96 - Elevated support printed concrete

Figure 97 - Elevated support printing resolution

§ 7.5.5 *Support net layer spraying*

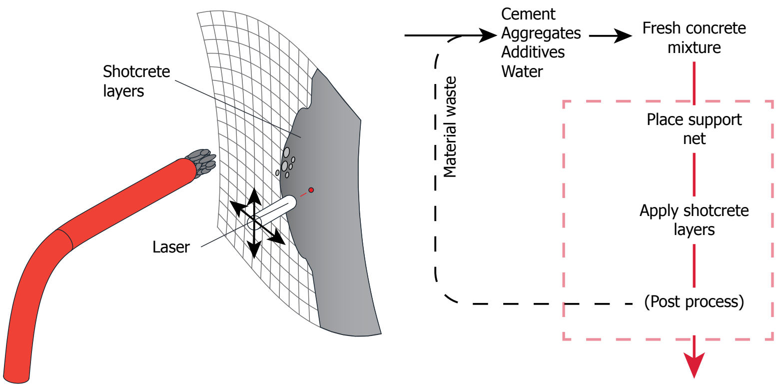


Figure 98 - Reinforcement / support net layer spraying

Support net spraying is a method that builds a layer around a core. It uses a frame that can also be used as reinforcement for defining the geometry of the AM element. The net is covered with concrete using a spray on technique. The amount of layers depends on the desired thickness. After the element has been cured it can be post processed to improve the surface quality.

<u>Advantageous properties:</u>

- Build around the embedded reinforcement.
- Freeform
- Optimised material usage

§ 7.6 *Advanced extruder*

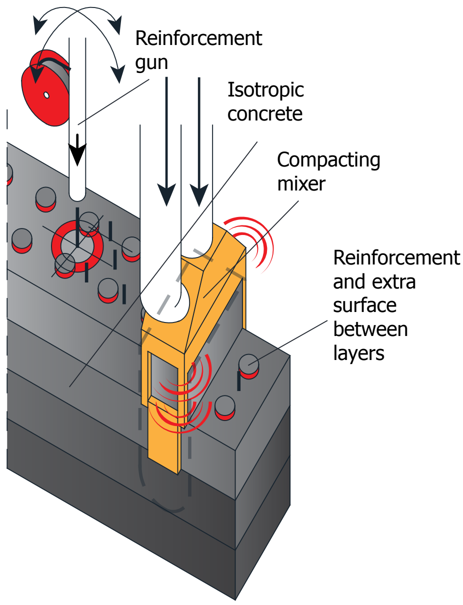


Figure 99 - Advanced extruder

The advanced extruder can be used as extrusion head in the future visions. It combines the previously mentioned developments in such a way that the material can be used in an optimised way. The inter layer strength, mixture and reinforcement orientation can be controlled. When the way of processing the material through a nozzle is controlled and combined with the right mixture the exact characteristics of the extruder can be adapted to the AM process.

Next to the ability to print gradient materials, the advanced extruder has, like in Contour Crafting, trowels that are used to smoothen the surface. In this way a smooth surface can be obtained without a time intensive high resolution. It is a sort of direct post processing that can also be used for compacting when the trowels vibrate.

An important instrument related to the advanced extruder is the G-code. It needs to be extended with additional information like the composition (§7.8).

§ 7.7 *Products*

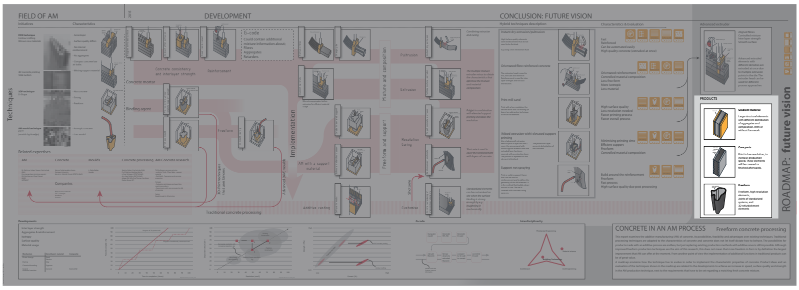


Figure 100 - Roadmap: products

The products that can be made with the new techniques should either be different from existing concrete products or the process has to be more efficient so that the production process is competitive, as described in chapter 6.

The products focus on freeform elements like façade cladding, small batch size with different forms (for example corner solutions for standardized elements) or large freeform extruded elements with embedded reinforcement. The reinforcement can also be shot in the concrete, which allows the industry to produce fibre aligned reinforced UHPC.

If the technique is used on site different densities of concrete can be applied using the advanced extruder head, if the mixture is relatively earth dry. The material is placed in such a way that over dimensioning or unnecessarily material usage is prevented.

An example of a product with internal structures like a human bone (figure 80) can be seen in figures 102 and 103. This gypsum model is 3D printed. With this AM technique it is possible to print at a very high resolution and to use this for the internal structure. However it is faster and more economical to change the mixture, using expanded glass balls or by using a raising agent. The internal voids shown in figure 103 are made with a gypsum 3DP technology, but figure 104 shows foam concrete that has nearly the same result. This is why different mixtures are more suitable in a fast economic concrete extrusion process.

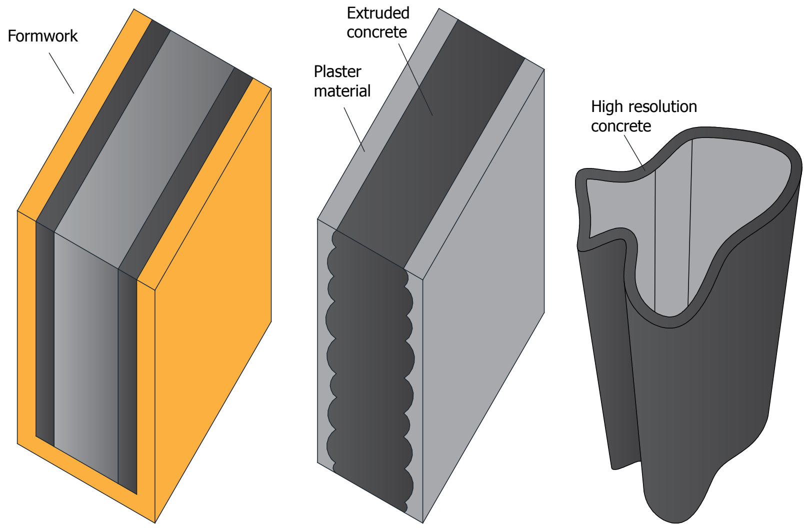


Figure 101 - f.l.t.r. Gradient concrete in mould, an element that is finished afterwards and a freeform element

Products can be:

- Gradient concrete elements (insulation and material efficiency),
- Lower resolution freeform structures that are finished,
- Freeform elements (economically small batch sizes), and
- Freeform elements that can not be made otherwise (internal voids).

The hybrid production techniques have also a high potential at the moment, while complete freedom in form without formwork is pursued. Combining different techniques in such a way that only the beneficial properties are used shows its potentials in AM casting in formwork. (figure 101 left). It adds extra functions to a widely used product. These functions can be:

- Insulation (porous concrete in the middle),
- Structural optimisation (material usage),
- Controlled fibre reinforcement disposition without the need of pre-installed nets.

§ 7.7.1 *Gradient materialized composite elements*

Gradient material elements can be obtained in different ways;

- Printing the structure
- By chemical reaction in the concrete that foams the concrete
- By lightweight aggregates.

Figure 98 and 99 show a 3D-printed gypsum element with a gradient. This open structure inside has been modelled in the computer and is not randomly like in the foam concrete (figure 101) or concrete with expanded glass balls. For concrete the randomly distributed voids to obtain the gradient are the best solution since printing them needs a very high resolution and is time intensive.

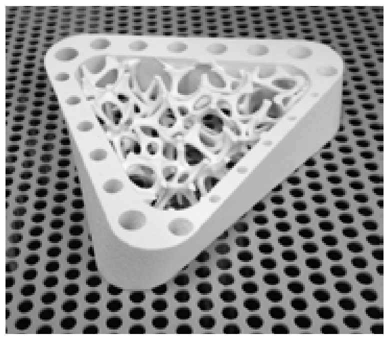


Figure 102 (left) - Section of façade element with integrated heat exchanger (Computer model).

Figure 103 (right) - Printed gypsum model. of the integrated heat exchanger

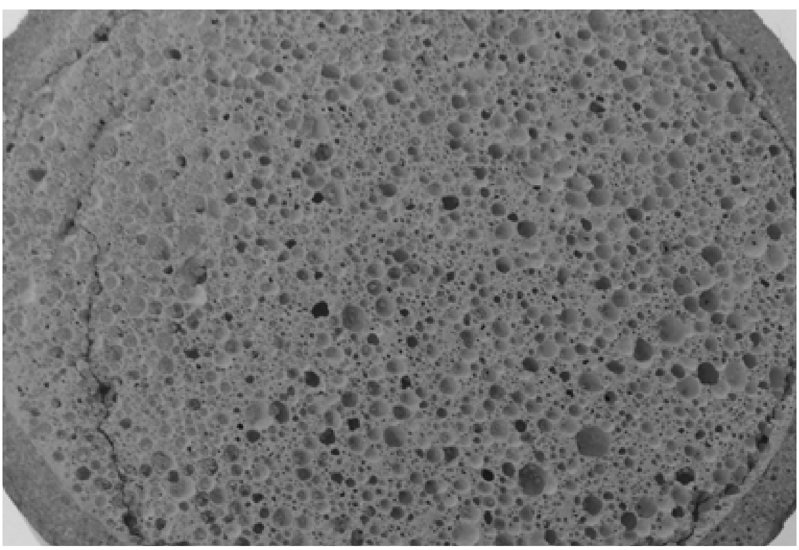


Figure 104 - Foam concrete

Figure 105 - Concrete core with expanded glass balls

§ 7.8 *G-code*

Printing with a composite that hardens according to a chemical reaction asks for another extrusion approach. First of all a gradient material that is mixed just before extrusion is new. If the material properties differ along the extrusion path, additional information regarding the composition of the material and the filament thickness after extrusion is needed. This information about the mixture can be saved in a parallel G-code like temperature is done for an FDM process as illustrated in figure 106. In plastic FDM the printer is calibrated for a certain material, with a certain filament thickness. The layer thickness is known and the software adjusts the printer nozzle according to these constant values. If the material composition differs along the extrusion path, additional sensors to observe the extruded filament are necessary. If the extruded element is not scanned before another layer is extruded, the model can collapse. Using a continuously updated G-code is needed to process gradient materials.

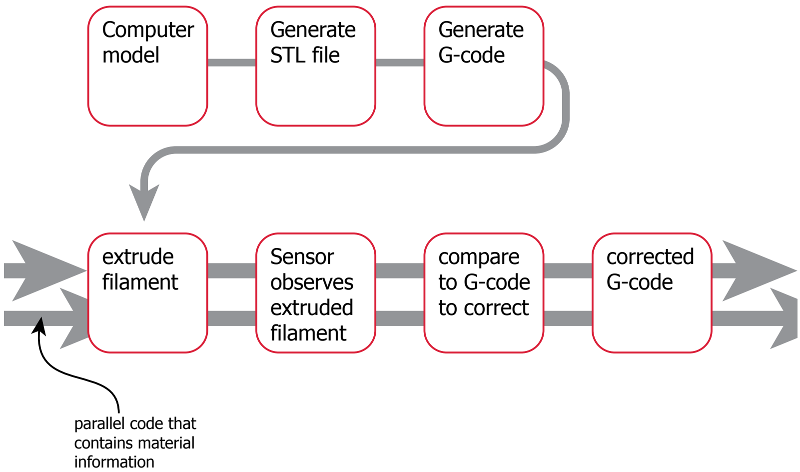


Figure 106 - Correcting G-code during extrusion

§ 7.9 *Conclusions roadmap*

The roadmap shows a clear representation of the current technical situation, the expected developments, the relation between existing AM techniques and those used for AM of concrete and a founded future vision with matching products. Most important is the relation between the characteristics of concrete and the production process. Concrete cannot be processed without adapting an AM process to it, as its behaviour differs too much from, for example, plastics. The five visions show how concrete can be processed in the future. It tries to solve the problem with reinforcement, aggregates and the weak inter layer strength. The products that match the production processes are divided in groups;

- Elements that will be post processed,
- High resolution free form elements, and
- Elements casted with use of AM in formwork to create gradient materials

Although it is possible to print everything, it is important to use the technique adequate. When there is no direct economical benefit, added value needs to be pursued.

III Conclusions

8 Conclusions and recommendations

§ 8.1 *Conclusions*

While answering the research questions, it became clear that the main challenge of the AM of concrete is how the technique is used and the way the concrete is processed. The roadmap shows a summary of the existing processes and how they should evolve. The overall strength, inter layer strength, reinforcement and the material composition are aspects that need to be developed first. The future vision showed five techniques that respect the characteristics of concrete and most sub-questions regarding the evolvement of the technique are answered within these visions. The questions about how to implement the technique in the building process are harder to answer, because a well functioning technique as a freeform concrete processing principle does not exist yet. It is premature to talk about specific characteristics of the elements and whether the AM should take place at the building site or not, therefore a shift in research focus to processes has to be made. Nonetheless, it can be assumed with certainty that the production technique will develop in two directions in the near future. One for large elements that only can be produced on site and on the other hand the high resolution elements that need to be made in a controlled environment for best results.

Requirements of products are nevertheless important to evolve the production technique and to examine the designed production process. Attention need to be paid that the AM technique is used adequate.

AM of concrete is a challenging field. The material and the manner of processing are just a first stage. Considering that the strength of concrete is its price, the prevailing approach to the AM of concrete, which consists of producing relatively low strength elements by a lot of expensive cement, is ineffective. To improve this the material and processing process needs to be integrated. Concrete differs in many ways from the materials that are commonly used in AM processes, due to the chemical reaction involved.

The way concrete is processed by initiatives such as Contour Crafting, 3D-Concrete printing impose on concrete a production technique that looks like Fused Deposit Melting. D-Shape uses just like 3D-printing a binding agent. All those methods do not use concrete as described in literature, but rather as a substitute for normal concrete in order to sell it. The material and the process should be changed to get the best results, but as far as information is available that is not done yet. The findings in this thesis indicate that to get the best results the materials and

processes used in present AM methods need to be changed and more aligned.
The possibilities for products made with an additive process are endless, but to improve existing production methods with the use of additive ones, does not mean that more freedom in form is the largest improvement. From another point of view implementation of functions in traditional products can be even more valuable. An example is the integration of insulation in the core of casted walls, using AM to extrude these porous cores in between of the water tight and load bearing slabs.
Freeform elements can also be made using an advanced moulding technique. Internal gradient properties cannot made otherwise.
Added value is the aim that should be pursued in an AM process. AM has a great potential for the concrete industry, but the application is in some cases less visible, since implementation of functions is not always as visible as freeform geometry.

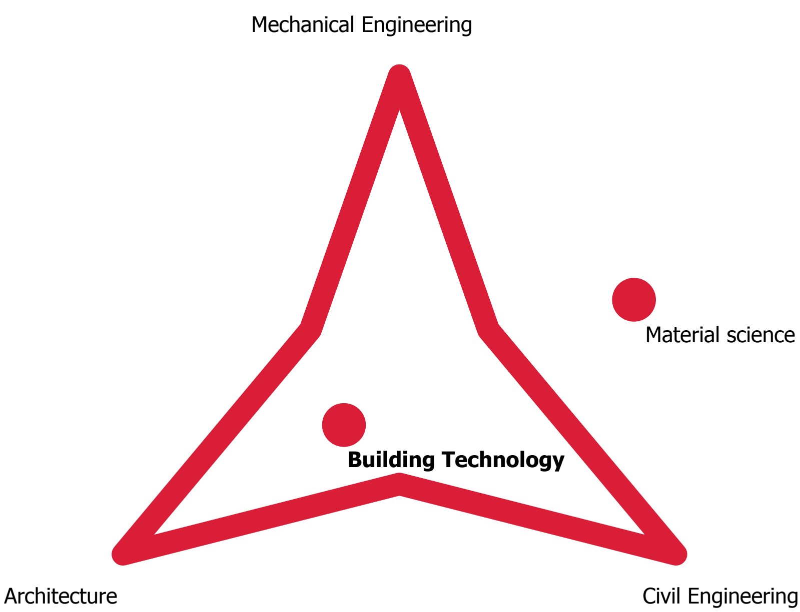


Figure 107 - AM of concrete as interdisciplinary subject

§ 8.2 *Recommendations*

Although this thesis has described various difficulties, printing concrete remains a viable technique, however it still requires a lot of research. Especially to make it economically feasible it is important to be able to compete with traditional and more advanced concrete processing techniques, including approaches that leads to freeform concrete elements as well: in particular the AM of moulds.

The roadmap shows how AM of concrete should evolve. Milling, printing support structures, using different approaches for support and pultrusion with an adaptable die are part of the roadmap. The main conclusion is that production techniques need to be combined for processing the composite material.

However this is a vision and the final processing methods could differ. A collaboration between mechanical engineering, civil engineering, material science, architecture and building technology in the middle of them to coordinate would be the best way to share knowledge and get the desired result:

- A machine capable of the requirements - Mechanical engineering,
- The right mixture (Properties and reinforcement) - Civil engineering / Material science,
- Architectural products that benefit most from the possibilities that this technique has to offer - Architecture,
- Structural products that benefit most from the possibilities that this technique has to offer - Civil engineering, and
- A life cycle assessment - Civil engineering, Material science and Architecture.

In a time where everyone is trying to obtain patents it is important to get at the same level of knowledge. Now is the time to join forces to gather and share the knowledge available within the university.

The recommendations are mostly about the way a project like this should be organised. The subject is very broad and gives room for multiple faculties to join. However collaboration is a key factor, it is also important that ideas and concepts are validated by producing elements and testing them.

Appendices

Appendix 1 - Experiment with layered concrete
Appendix 2 - Printed mould
Appendix 3 - Decomposition of concrete mixture
Appendix 4 - Capillary action 3D-printing with water
Appendix 5 - Extruding on bentonite
Appendix 6 - Aligned fibre reinforcement
Appendix 7 - Elevated support printing
Appendix 8 - Gradient concrete
Appendix 9 - Technology roadmap by Volkers

A1 *Experiment with layered concrete*

Test layered concrete BEAmix 135

Using 150/150/150mm cubes to look at the difference between layered and single volume casted elements.

Experiment:

Casting 8 elements with BEAmix 135

2 compacted cubes with concrete

2 not compacted 5 layers (30mm each) concrete cube

2 compacted 5 layers (30mm each) concrete cube

The time interval between the layers is 5 minutes to simulate a layered extrusion process, and determine if the open time next to the layers influences the concrete's strength.

After curing the concrete will has been tested on compressive strength.

Figure A1 (left) - Casted cubes

Figure A2 (right) - De-moulded cubes

	compacted cube	layered compacted cube	layered cube
7 day strength (27 may 2014)	28.58MPa	28.41MPa	23.2MPa
28 days strength	?	?	?
surface	smooth	smooth	rough
consistency	normal	normal	with voids

Table A1 - Strength demoulded cubes

Tension strength is normally 10% of the compressive strength

Flexural strength is approximately 15% of the compressive strength

A2 *Printed mould*

To test the surface quality BEAmix 135 has been casted on a 3D printed ABS element placed inside an 150/150/150 mould. The surface shows the relief of the resolution of the printed mould, although it had been sanded and treated with diluted acetone. There is also a lot of capillary voids in the mixture that showed up at the surface. Either the mixture was too wet or more compacting had been needed. Demoulding was hard due the 90 degrees angles and the stacked filaments that acted as hooks. 2 - 5 degrees tapered walls would ease the de-moulding like a ring shaped cake.

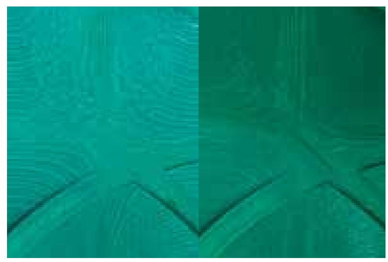



Figure A3 (left) - Part of the mould printed out of ABS

Figure A4 (right) - Before and after sanding the mould a little


Figure A5 (left) - Cured concrete with locked mould

Figure A6 (right) - De-moulded element

Printing advanced moulds has also to do with these design limitations, limiting the freedom in form.

A3 *Decomposition of the concrete mixture*

Figure A5 (left) - Mortar extruder

Figure A6 (right) - Extrusion of mortar with bentonite

The sealant gun applies to much force on the thick mortar to be extruded well. The mixture decomposes and the sealant gun gets clogged. Mortar mixed with bentonite does not clog the sealant gun and forms can be extruded easily, but hardens slowly.

A4 *Capillary action 3D-printing with water*

Figure A7 (left) - Spraying water on concrete mix

Figure A8 (right) - Brittle concrete after drying

Spraying water on spread concrete should only bind the concrete that gets wet. Because it is not mixed well the capillary action the concrete becomes brittle. The water/cement factor is too low, but the air that is normally removed during mixing and compacting is still within the cured concrete and is the main cause of the brittleness.

A5 *Extruding on bentonite*

Bentonite is a material used to prevent excavations from collapsing. The muddy substance is poured in the cavity till the desired depth is reached. After the excavation concrete is poured in the cavity. The density of concrete is higher and the bentonite will float on the concrete.

By changing the amount of water the density of the bentonite mixture can be adapted. Concrete with a normal density of 2250 kg/m^3 remains to heavy to float on bentonite. Although bentonite has some surface tension the concrete sinks if a thick layer of concrete is applied.

Figure A9 (left) - Concrete with bentonite as support material

Figure A10 (right) - Layered concrete with rough surface

The experiment is repeated with sand. The way of processing differs. Was bentonite orinting meant like NSTRMNT (§3.2.5), printing with sand is a combination of 3DP and an FDM process.

A7 *Aligned fibre reinforcement*

To examine whether it is possible and how fibre reinforced concrete would look like, formwork has been used. The fibres are concentrated in the bottom part of the concrete. Figures A11, A12 and A13, show the formwork and casted concrete element.

Figure A11 (left) - Formwork with fibres

Figure A12 (right) - Concrete cube with fibre reinforcement

Figure A12 - Close-up fibres

A7 *Elevated support printing*

Elevated support printing has been tested with a concrete mortar. The mortar consisted of 30% cement and 70% sand. After the first layer was extruded, sand was added as support material. After a few layers the small concrete dome's roof was closed (figures A13, A14 and A15) Unfortunately the sealant gun still gets clogged rapidly. Despite that the method works. If an advanced extruder is used freeform elements can be made easily.


Figure A13 (left) - First layer

Figure A14 (right) - Supported layer


Figure A14 (left) - Finished dome

Figure A15 (right) - ‘demoulded’ element


Figure A16 (left) - Bottom of the element

Figure A17 (right) - Resolution of extrusion process

A8 *Gradient concrete*

3 types of gradient concrete were made. One of them was casted at once (figure A18) the last two were casted with 30 minutes between the outside and inside of the element (figures A19 and A20). The elements are not tested, but show to be rigid. The mixture used for the element in figure A20 contained less cement for the core. It is more porous but sticks well together.

Figure A18 (left) - Two types of concrete casted at once

Figure A19 (right) - Two types of concrete casted with 30 minutes in between

Figure A20 - Two types of concrete casted with 30 minutes in between.

A9 Technology roadmap by Volkers

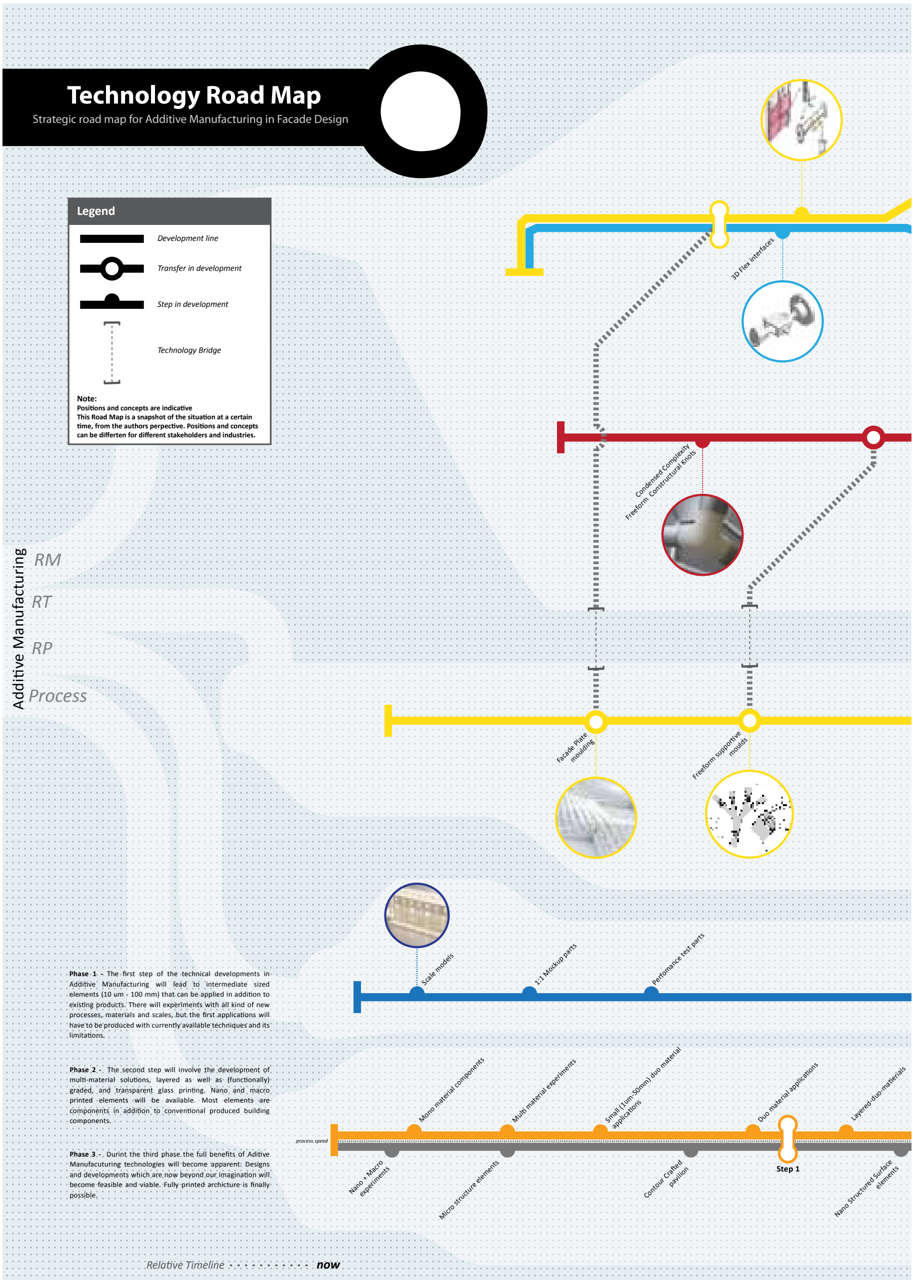
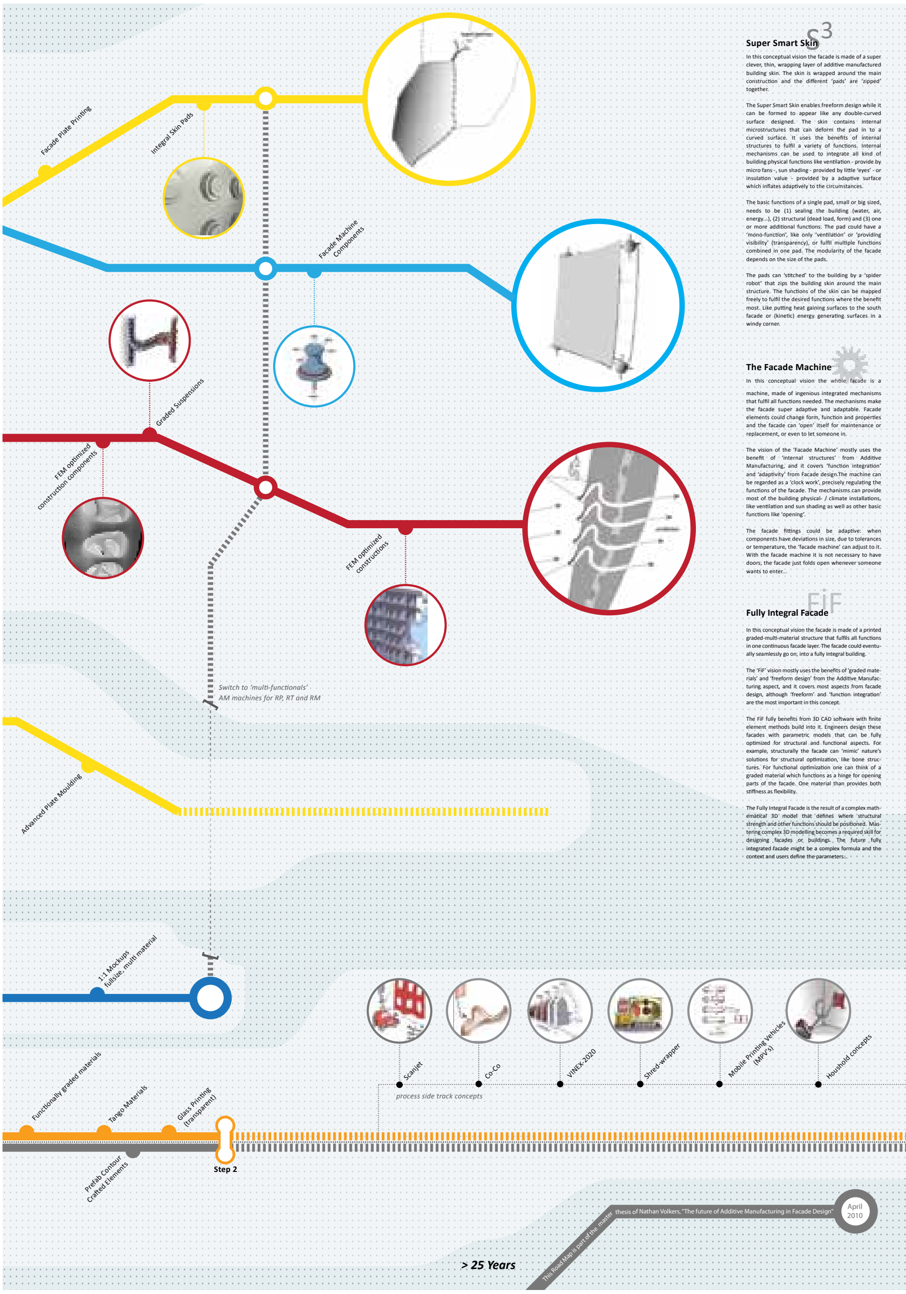


Figure A21 - Technology Roadmap by Volkers[(1)]

[1] *Volkers, N., 2010, p. 109*



Super Smart Skin

In this conceptual vision the facade is made of a super clever, thin, wrapping layer of additive manufactured building skin. The skin is wrapped around the main construction and the different 'pads' are 'zipped' together.

The Super Smart Skin enables freeform design while it can be formed to appear like any double-curved surface designed. The skin contains internal microstructures that can deform the pad in to a curved surface. It uses the benefits of internal structures to fulfil a variety of functions. Internal mechanisms can be used to integrate all kind of building physical functions like ventilation - provide by micro fans -, sun shading - provided by little 'eyes' - or insulation value - provided by a adaptive surface which inflates adaptively to the circumstances.

The basic functions of a single pad, small or big sized, needs to be (1) sealing the building (water, air, energy...), (2) structural (dead load, form) and (3) one or more additional functions. The pad could have a 'mono-function', like only 'ventilation' or 'providing visibility' (transparency), or fulfil multiple functions combined in one pad. The modularity of the facade depends on the size of the pads.

The pads can 'stitched' to the building by a 'spider robot' that zips the building skin around the main structure. The functions of the skin can be mapped freely to fulfil the desired functions where the benefit most. Like putting heat gaining surfaces to the south facade or (kinetic) energy generating surfaces in a windy corner.

The Facade Machine

In this conceptual vision the whole facade is a machine, made of ingenious integrated mechanisms that fulfil all functions needed. The mechanisms make the facade super adaptive and adaptable. Facade elements could change form, function and properties and the facade can 'open' itself for maintenance or replacement, or even to let someone in.

The vision of the 'Facade Machine' mostly uses the benefit of 'internal structures' from Additive Manufacturing, and it covers 'function integration' and 'adaptivity' from Facade design.The machine can be regarded as a 'clock work', precisely regulating the functions of the facade. The mechanisms can provide most of the building physical- / climate installations, like ventilation and sun shading as well as other basic functions like 'opening'.

The facade fittings could be adaptive: when components have deviations in size, due to tolerances or temperature, the 'facade machine' can adjust to it. With the facade machine it is not necessary to have doors, the facade just folds open whenever someone wants to enter...

Fully Integral Facade

In this conceptual vision the facade is made of a printed graded-multi-material structure that fulfils all functions in one continuous facade layer. The facade could eventually seamlessly go on, into a fully integral building.

The 'FiF' vision mostly uses the benefits of 'graded materials' and 'freeform design' from the Additive Manufacturing aspect, and it covers most aspects from facade design, although 'freeform' and 'function integration' are the most important in this concept.

The FiF fully benefits from 3D CAD software with finite element methods build into it. Engineers design these facades with parametric models that can be fully optimized for structural and functional aspects. For example, structurally the facade can 'mimic' nature's solutions for structural optimization, like bone structures. For functional optimization one can think of a graded material which functions as a hinge for opening parts of the facade. One material than provides both stiffness as flexibility.

The Fully Integral Facade is the result of a complex mathematical 3D model that defines where structural strength and other functions should be positioned. Mastering complex 3D modelling becomes a required skill for designing facades or buildings. The future fully integrated facade might be a complex formula and the context and users define the parameters...

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Glossary

3DP	3D-printing
AM	Additive Manufacturing
CC	Contour Crafting
Earth dry	Fresh concrete with a very low water cement ratio
FDM	Fused Deposition Modelling
Filament	Line-like material used to extrude
Fresh concrete	Mixed ingredients of the composite before curing
G-code	Code that describes the path of an extrusion head
Green ceramic body	Dried clay element
Green strength	High strength at early life of concrete
LCA	Life Cycle Assessment
LS	Laser Sintering
Plasticizer	Additive in fresh concrete to make it more workable
Polyjet	An AM process that uses multiple nozzles to build a model
Retarder	Additive in fresh concrete to make cure more slowly
Silica	Fine powder that also binds the mixture
Shotcrete	Concrete that is sprayed against objects
SLA	Stereolithography
UHPC	Ultra High Performance Concrete
UHPFRC	Ultra High Performance Fibre Reinforced Concrete
WCR	Water Cement Ratio
Workability	The ease of processing the material
Zappie	A material that has only advantageous properties. This material is used often in the AE+T department

in an AM process

This report examines the additive manufacturing (AM) of concrete, its possibilities, feasibility and advantages over existing techniques. The possibilities for products made with an additive process are endless, but just replacing existing production methods with additive ones is still impossible. Although improved freeform production techniques are the aim of this research, this does not mean that more freedom in form is by definition the largest improvement that AM can offer at the moment. From another point of view the implementation of additional functions in traditional products can be of great value.

A roadmap envisions how the technique has to evolve in order to implement the characteristic properties of concrete. Product ideas and an evaluation of the techniques shown in the roadmap are related to the developments to achieve an increase in speed, surface quality and strength in the AM production technique, next to the requirements that have to be set regarding a matching fresh concrete mixture.

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