AGING ARCHITECTURE

WEATHERING SIMULATION

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Research work at the TU Eindhoven DDSS laboratory
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ABSTRACT

All architectural sites are changing in appearance when exposed to the conditions of the surrounding environment. External materials suffer from weathering effects that damage both their surface and composition. This research work presents an approach for the modeling and rendering of an aging architecture simulation.

In computer graphics, a way to obtain more realistic results consists of adding imperfections such as dirt, dust, scratches on the objects in order to avoid an ideally looking. In most of the cases artists use a technique like painting to reach these results. In this work we will implement imperfections directly in the simulation depending on the environmental factors of weathering. Our goal is certainly not to give an accurate prediction of the future appearance of the building but rather to identify weathering factors and show their effect on the building.

The first approach identifies different ages of the materials and by going from one to another the time-dependent material is created. In order to improve the basic simulation to an advanced weathering simulation, we propose to simulate impact points on the objects: particles representing rain are emitted from an abstract sky, and they create marks where they hit the objects. These marks involve local weathering.

Moreover environmental factors such as dirt, dust, moisture deposits are also changing the appearance of the building, and therefore must be represented. These factors are listed separately in order to be flexible in any further simulation.

Using some virtual models we explain the proceedings to set up the aging materials and the environmental factors. Since these data can be saved in a library, and later easily loaded, the library can be completed and shared, that improving the accuracy of weathering simulations.

A final test on an existing sculpture element compares simulated and existing results using this method. A possibility of communication of this simulation is through a 3D interactive environment and time-dependent, this relates to a 4D interactive simulation.

Note:
all of these renderings used the materials that are on the CD with nothing additional. Using these materials on wide surfaces does not give real results, it can be improved by adding extra filter or noise onto the surface. The purpose of the research was to create a standard material that might be slightly edited in renderings to match realistic results in the desired scene.

Rendering, memory and hardware expenses:
All these simulations were run on a 3,40GHz Pentium 4 CPU running windows XP SP2, with 2.00 GB of RAM.

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“THE WATER HOLLOWED THE STONE,
THE WIND DISPERSED THE WATER,
THE STONE STOPPED THE WIND,
WATER AND WIND AND STONE”

Octavio PAZ, *“A draft of shadows”*,
quoted in *“On Weathering, the Life of Buildings in Time”*

INTRODUCTION

About weathering

All materials are weathering. When exposed to the conditions of the surrounding environment, surfaces are changing in appearance and composition in the time. This deterioration is obvious, and takes a commonplace in Architecture. Buildings are erected to persist in time, but no building can stand forever because of the gradual destruction by nature, called weathering. Mostafavi and Leatherbarrow [01] resumed the building life as *"Finishing ends construction, weathering constructs finishes. (…) Our argument is to revise the sense of the ending of an architectural project, not to see finishing as the final moment of construction but to see the unending deterioration of a finish that results from weathering".*

A definition of the term weathering was elaborated by Simpson and Horrobin [02] *"Some authorities refer to weathering as the action of both the natural climate and atmospheric pollution, together with any other extraneous influences."* Weathering is the deterioration caused by its natural climate, synonymous of environment. It can be seen in the form of dirt, scratches, dust, erosion, cracks, moss and other aspects that are changing the appearance of the building in time. In other words, weathering does not construct, it destroys. Weathering makes the building aging by subtracting "finishes" of it, and following Mostafavi and Leatherbarrow [01] *"In the process of subtracting the "finish" of a construction, weathering adds the "finish" of the environment."* But weathering does not only degrade buildings. As weathering effects are common, can the environment effects enhance the appearance of the building? Most of our architectural monuments relate history and time because of their weathered surface imperfections catching the human eye. What would be our response in front of a sharp edge Doric column, without any failure and a small amount of light green lichen on the rough surface? This appearance makes the visitor understanding that these stones are 2000 years old.

For architects, weathering should be also a design factor: some knowledge about weathering causes and effects might avoid premature degradation. Moreover, considering that weathering affects all the surfaces and always leaves marks, architects may use these marks as an intended or even desired future building appearance, as far as they can predict these effects.

Figure 1 Villa Savoye 1929-1931 (Le Corbusier): state before restoration (1963-1997). Source: *"On Weathering, the Life of Buildings in Time"*

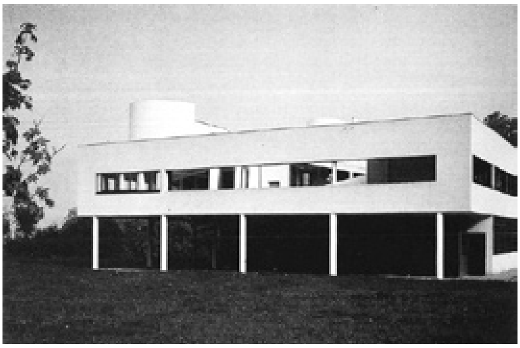


Figure 2 Villa Savoye 1929-1931 (Le Corbusier): state after restoration (1963-1997). Source: *"On Weathering, the Life of Buildings in Time"*

Delaying the weathering effects requires a specific design and attention on the surfaces. Deterioration was delayed in traditional buildings through the incorporation of elements that restricted direct exposure to rainwater, and eventually to sunlight. Generally, adding details affects the weathering effects and the visual appearance. Placing a cornice at the top part of a façade was a widely used architectural element from antiquity till neo-classicism, first in order to throw off the rainwater, which later also became the status of an ornament. Unfortunately, the mass construction movement starting in the 20th century, providing wide and white flat walls, led to premature degradation especially in the early modern buildings [01]. An early breakdown of the materials and increased stain deposit are the most relevant examples.

Notable architectural details can be found in Carlo Scarpa's work. These details show a creative transformation of traditional elements, based on weathering effects and surface future appearance. Mostafari and Leatherbarrow [01] commented a detail on the windows (figure 3) from the Banca Popolare di Verona *: "at the bottom of each of the circular windows is a vertical line running in the direction of the likely flow of rainwater".*

By guiding the rainwater, this detail incorporates and controls stain and dirt deposit on the façade. In the Brion cemetery, Scarpa interrupted

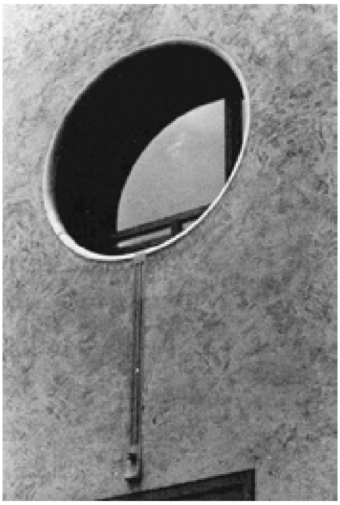


Figure 3 Banca Popolare di Verona, window detail 1974-1981 (Carlo Scarpa). Source: “On Weathering, the Life of Buildings in Time”

Figure 4 Brion cemetery 1970-1981 (Carlo Scarpa). Source: “On Weathering, the Life of Buildings in Time”

the horizontal run on the tall, blank exterior wall of the chapel (figure 4). The gap involved shows the effects of weathering allowing the rainwater to seep through, leaving a black stain in the middle of the wall. This mark reveals the life of the building in the time.

Weathering is obvious, affects all architectural elements, and makes the surface of a building ever-changing. This breakdown, that proceeds uninterrupted, leads to the failure of materials and the final dissolution of the building itself. Unfortunately the variations in the weather depending on the location prohibit generalizing the weathering effects.

Purpose of this research and simulation

Techniques in computer graphics have reached the point to produce realistic images today. Mainly developed for game and movie industries, architects and urban planners use it to visualize their projects: [03] *“The architect design is divided in the creative part and exploration observation part”*. But this communication tool looks often too ideal, and does not always present a natural look.

On the other hand, rendering imperfection techniques took an important place in rendering simulations during the last years. Following Even and Gobron [04] *"Computer graphics literature about surface imperfections rendering covers a wide range of impressive effects such as corrosion, weathered stone, impacts, scratches and more recently lichen growth"*. Unfortunately those approaches are not specialized for architectural issues. Moreover, most of them have been tested on a unique model created for this purpose.

Adding weathering effects such as blemishes or stain to a simulation improves the quality to realistic results, because these effects appear everywhere in our daily life. One of the most straight-forward approaches is to simply generate detailed textures and object «by hand»: [05] *"traditionally, blemishes are generated by combining many hand-painted textures"*. This technique is a very time-consuming and difficult task that can be performed only by gifted artists and designers, also a weathering animation will demand days of painting to reach a result where a progressive variation is not guaranteed.

In this research we use this technology and expand it to the field of Architecture, in order to accomplish an aging simulation for Architecture. The goal is certainly not to give an accurate prediction of the future appearance but rather to present the possible degradations of a building under the environment effects.

Furthermore such a simulation can give an estimation of the durability of the building, as well as the future maintenance costs. Oxand, a firm expert in risk management for aging civil engineering infrastructures considers durability and lifetime of buildings as [A] *"the period during which it safely fulfils the functions for which it was built, taking into account operating conditions and economic requirements"*. Building costs are not insignificant in construction but while speaking about durability, costs become the sum of building act, repairing and maintenance, and finally disposal. Improving durability means using long life products which age with grace [06]. COWI is a consultant company within engineering, environmental science and economics which aims in improving the buildings durability [D] *"the operational approach to design for durability is to define durability as a service life requirement. In this way, the non-factual and rather subjective concept of 'durability' is transformed into a factual requirement of a number of years during which the structure performs satisfactory without unforeseen high costs for maintenance. In*

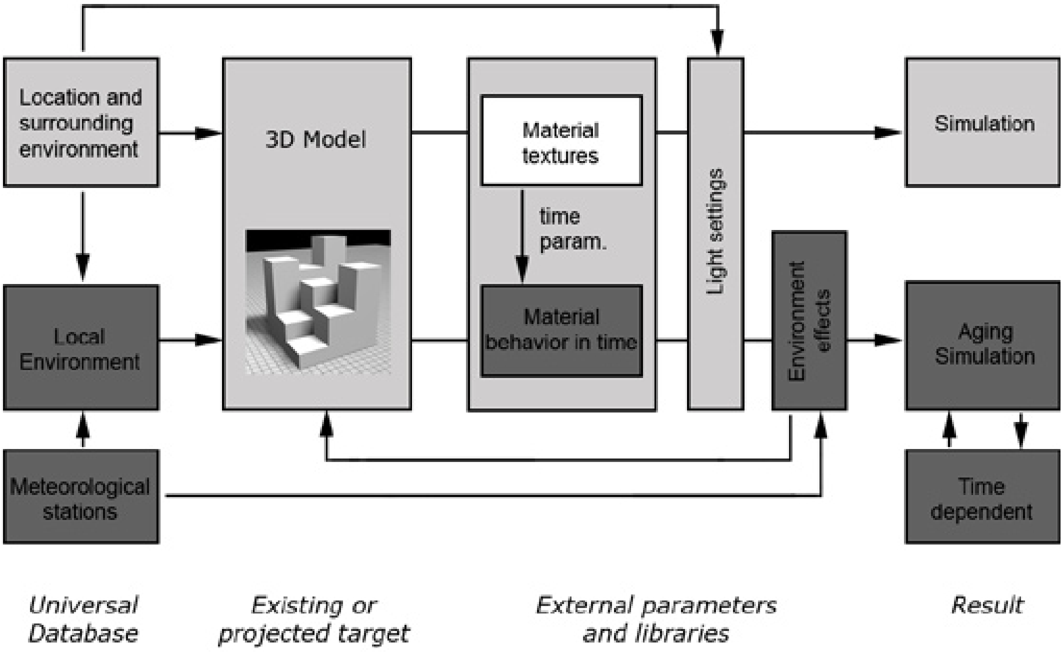


Figure 5: a general schema compares the workflows of a basic simulation and the additional steps to obtain an aging simulation

this way, the time factor is introduced as a design parameter". Today including maintenance costs as a design parameter is rarely considered mainly because of insufficient knowledge or inappropriate methodology. Even if construction can take several years, the building life can not be neglected: *"Yet buildings are expected to last at least 60 years; bridges are designed to last 120 years."* [06]

In this research our simulations focus on the appearance and the visual aspect of surfaces and materials. Other factors such as structural defects can deteriorate the building, its external and internal appearance but the consideration of these causes requires a wide engineering background from research centers and manufacturers, and unfortunately taking these factors into consideration may consume too much time for our goal. We hence concentrate on the external degradation and the environment effects; internal degradation is mainly due to users, this kind of simulation requires a previous study on the users' behavior and movement.

Working tools and communication

The purpose of this work does not consist of creating special software but rather uses an existing visualization program and explores the possibilities it offers. Fore future users some parameters (e.g. material properties) can be saved in a library, and later opened on any computer. Our approach is to compile a set of parameters and events that reoccur in weathering simulations. The other parameters are prepared but have to be set manually in the simulation to fit with local parameter (e.g. location), and in a long range we imagine an extra program as a plug-in to guide the user through the settings.

There are three main distinct possibilities to communicate the results of such a simulation, each providing different issue:

♦ Images are presumably the easiest and fastest solution to provide results. As the main working resource, it offers a wide range of output data from quick preview to best quality results, keeping rendering time and final file size reasonable. Parameters and settings are quickly reached and changed, and unexpected results are less frequent than the following possibilities. Furthermore 3 or 4 pictures can display the key moments of a weathering sequence.

♦ Animation brings the sense of time that lacks in images by showing a fluent variation, but an animation is nothing more than a set of images one after each other in a short time. Animation requires more attention since the frames between the key frames will be automatically generated and rendered. By animating a camera's movement in the time, an animation is expressing a 4D representation, but it is increasingly longer to render and expensive in terms of computational times. Animated sequence experimentation showed that a fixed camera does not provide more than a set of pictures; observer comments assumed a lack of controls on the time and the position to visualize a global view or details.

♦ Virtual reality (VR) is an improved possibility to present results using the 'Desk Cave', a prototype available in the DDSS laboratory (figure 6). It aims at placing the observer in an immersive simulation: *"It is an immersed environment program, which includes a computer controlled by a set* *of wired or a 'magic wand', a position tracker, and a head-mounted stereoscopic display for three-dimensional visual output, immersed in a cube-like environment with a display projected on three to six sides of a box-like structure. Virtual Reality in the broader sense is used to describe the sense of reality as opposed to virtual space of any kind, imagined or real."* [03]


Figure 6: "The cave" available at the TU/e

By using Virtual Reality the user's movement is tracked in six degrees of freedom; the user can control both the movement and the perspective view in 3D space. The fourth dimension will be represented by an additional track bar to allow the user to explore the virtual model in time.

The prototype in the laboratory has four screens rendered in real time by two computers: one is rendering the left and the right side, the other one is rendering the front side and the bottom surface. The correct standpoint is obtained at a unique eyes position.

PREVIOUS AND RELATED WORKS

Working on 4D models

The first computer graphics appeared in 1963 when I. Sutherland invented the first tool to draw schemas (2 Dimensions) on a computer from a graphic pen (figure 7) [C].

Few years after D. Evans and I. Sutherland experimented to model different objects in 3D, they completed in a model of their own car in 1967 with the help of some students (figures 8). But 3D graphics have not been developed before the 80's mostly because of the expensiveness of technology.

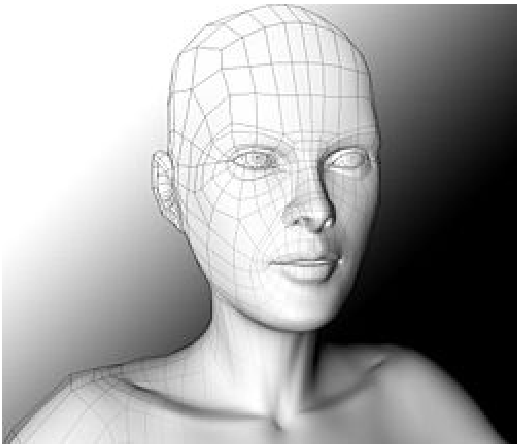


Figure 9: Development of 3D models from the early 90's
Source: http://fr.wikipedia.org/

Figure 7: First 2D graphics in 1963
Source: http://histoire.info.online.fr/

Figure 8: Experimentations on creating 3D models in 1967
Source: http://histoire.info.online.fr/

From the early years of the 90's, synthesized computer images are widely spread due to increased availability of cheap and more powerful computer hardware. Developed for computer games and movies industry, 3D models and renderings are now everywhere.

In this work we use a 3D model that will change in the time. Today working in 4D is a priority in some research works, the following examples show different domains in which 4D models are used:

♦ for acoustic studies (e.g. Groupe acoustique Clairbois Tisseyre), this research center creates 4D maps while comparing the noise emission from traffics (highway, trains and airports) (figure 10) nearby dwelling areas during the daytime, and creating schematic colored maps (figure 11) [D]

♦ to depict the geological layers initiation of the earth [E]

♦ to simulate organ movements and problems in medicine [F]

♦ to prevent risks of failure of structural materials, e.g. Oxand has developed the software SIMEO [A] to simulate future defects on concrete and steel in order to improve the material behavior in the time (figure 12).

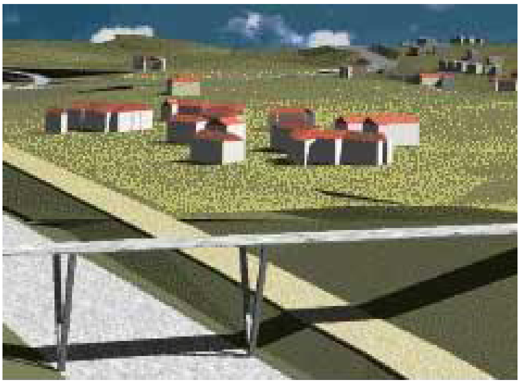


Figure 10: 3D models for acoustic studies
Source:
http://www.planete-acoustique.com/

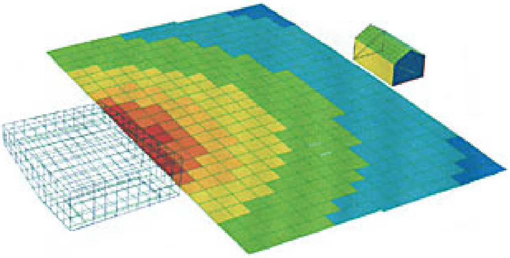


Figure 11: example of a noise map
Source:
http://www.planete-acoustique.com/

Figure 12: screenshot of the SIMEO software and examples of simulated results
Source: http://www.oxand.com/

♦ planning in construction: software already exists to link 3D model and planning to improve the project schedule communication; e.g. *Project 4D* from MIT [G] or 4D Suite from COMEPLAN (figure 13) [H]

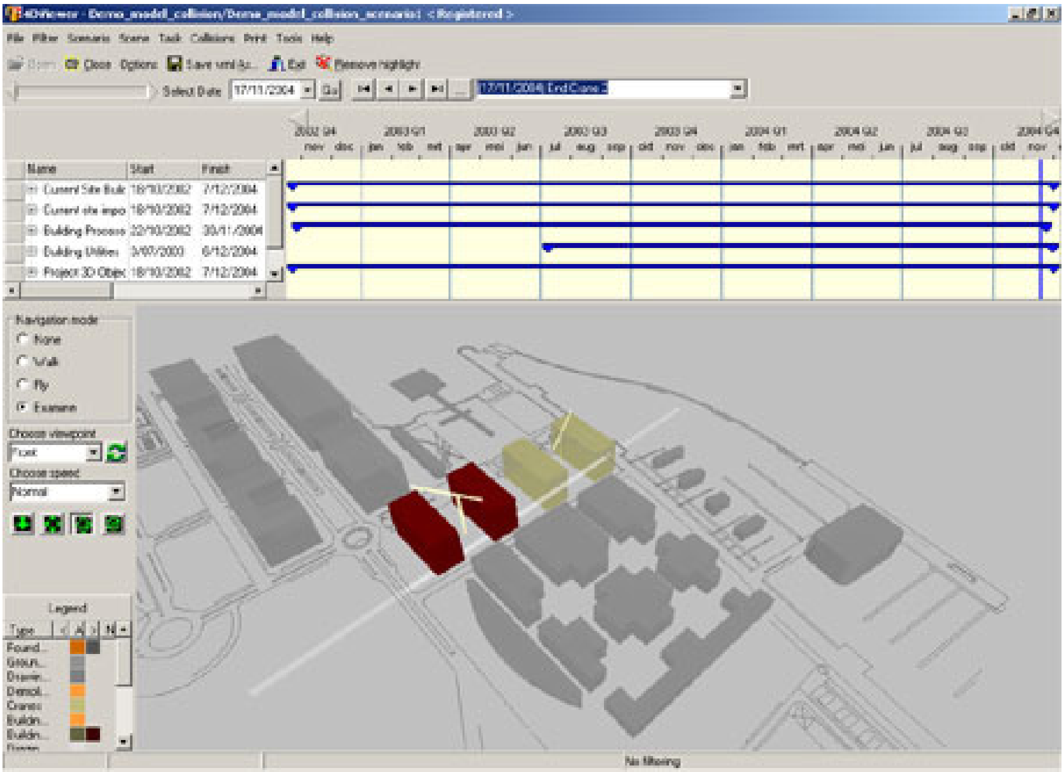


Figure 13: screenshot of the COMEPLAN software
Source: http://www.comeplan.be/

♦ VICO [I] is now improving software for 5D simulation including in the 3D model time and costs.

Previous and related works

Previous works can be identified in two categories: Modeling and rendering of weathering material and rendering imperfections from weathering.

J. Dorsey and P. Hanrahan were innovators in this area when they published their work *"Modeling and Rendering of Metallic Patinas"* [07] that is considered as a reference for any further research work. For the purpose to develop easily controllable models of weathered material, the example of metallic patinas was chosen. This formation or accumulation involved the use of different layers in the simulation, which evolve in the time to simulate deposit figure 14). Three different environments were investigated to compare the climate influence: marine, rural and urban. Three years later, this technique was applied to a weathering stone simulation [08]. The results were essentially based on the wetness of the material coupled to a water map and a deposit map. Both the surface and the interior material were represented in the simulation.

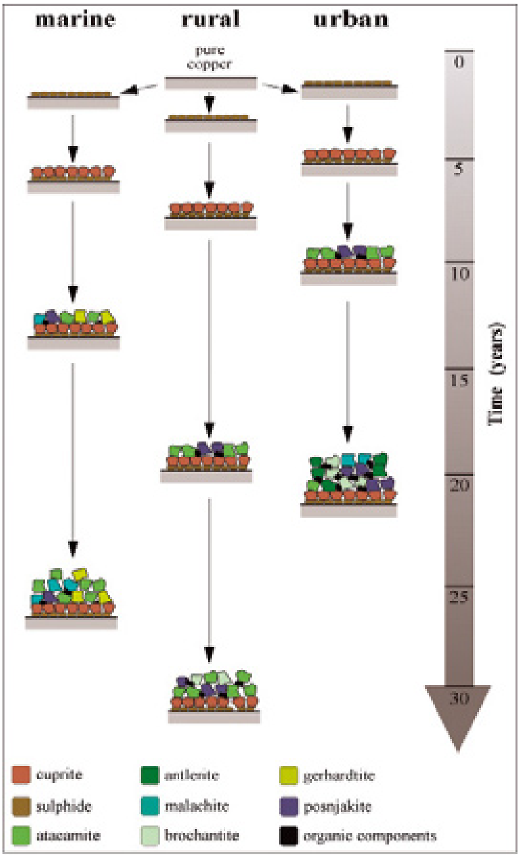


Figure 14: schematic diagram to simulate growth of copper patinas in marine, rural and urban environment

Figure 15: weathering sequence tested on a copper scultpure

Even and Gobron focused mainly on the environment effects from weathering on buildings [04], and especially on the surface: they clearly distinct the effects on the surface, the surface appearance changes and the surface geometry changes. Generating and applying special maps, the simulated effects are erosion, lampblack and vegetation growth (figures 16 & 17).

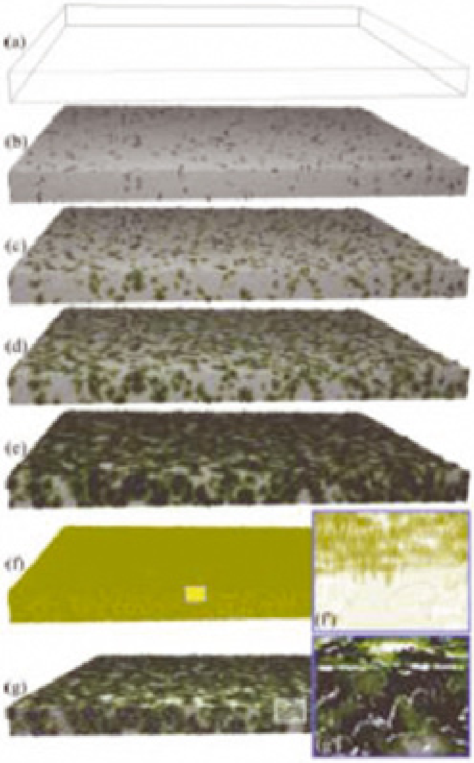


Figure 16: simulation of growing moss on a fractured surface

Figure 17: simulation of green lichen with stone erosion

A recent research work based on a type of aging-inducing particles created weathering simulation called «By γ-tons tracing” [ref03]. Thousands of γ-tons are shot in the scene, bounce and finally settle inducing weathering (figure 18). The position of γ-tons generates a γ-ton map, which then modify the surface materials properties and geometry through multi-texturing, texture synthesis, or displacement mapping. The possible motions of a γ-ton when hitting a surface are reflecting, bouncing, flowing or settle, depending on the carried energy. Out of settling, the γ-ton can pick up properties from the impact point and transport them to the next impact.

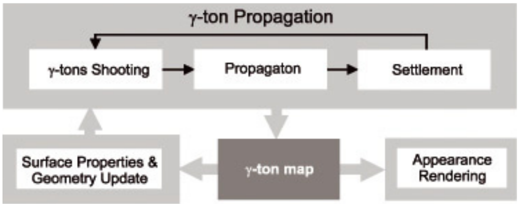


Figure 2: The overview of γ-ton tracing.

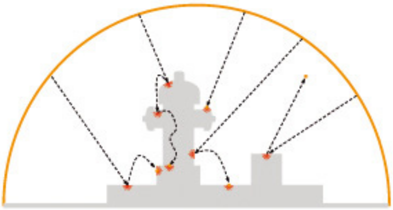


Figure 18: overview of the γ-ton tracing

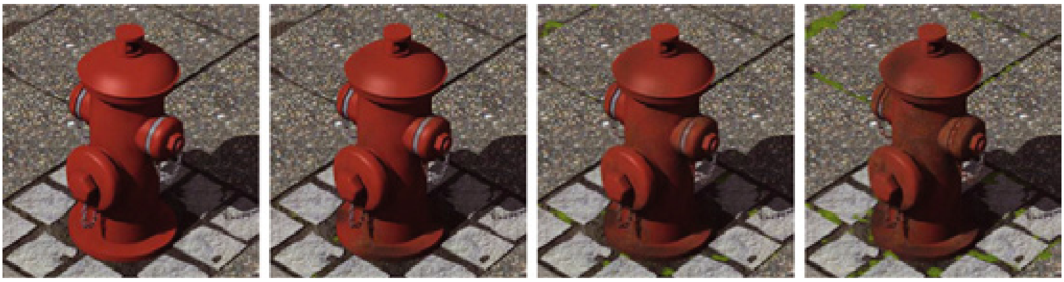


Figure 19: weathering sequence by γ-ton tracing

WEATHERING EFFECT SIMULATION: FROM DATA TO SIMULATION

Weathering factors and weathering effects

«If an instant weathering predictor would exist, the investigator would place a sample in the machine, switch on, and come back next day to find out how long the final product will last, having been stressed in every possible way, in every part of the world, under the sea, on mountain top, in the desert, in polluted cities, in space, in the tropics, in the arctic, in thunderstorms, in hurricanes, and in all seasons. The machine tells you how the product will fail and how to fix it.» [06]

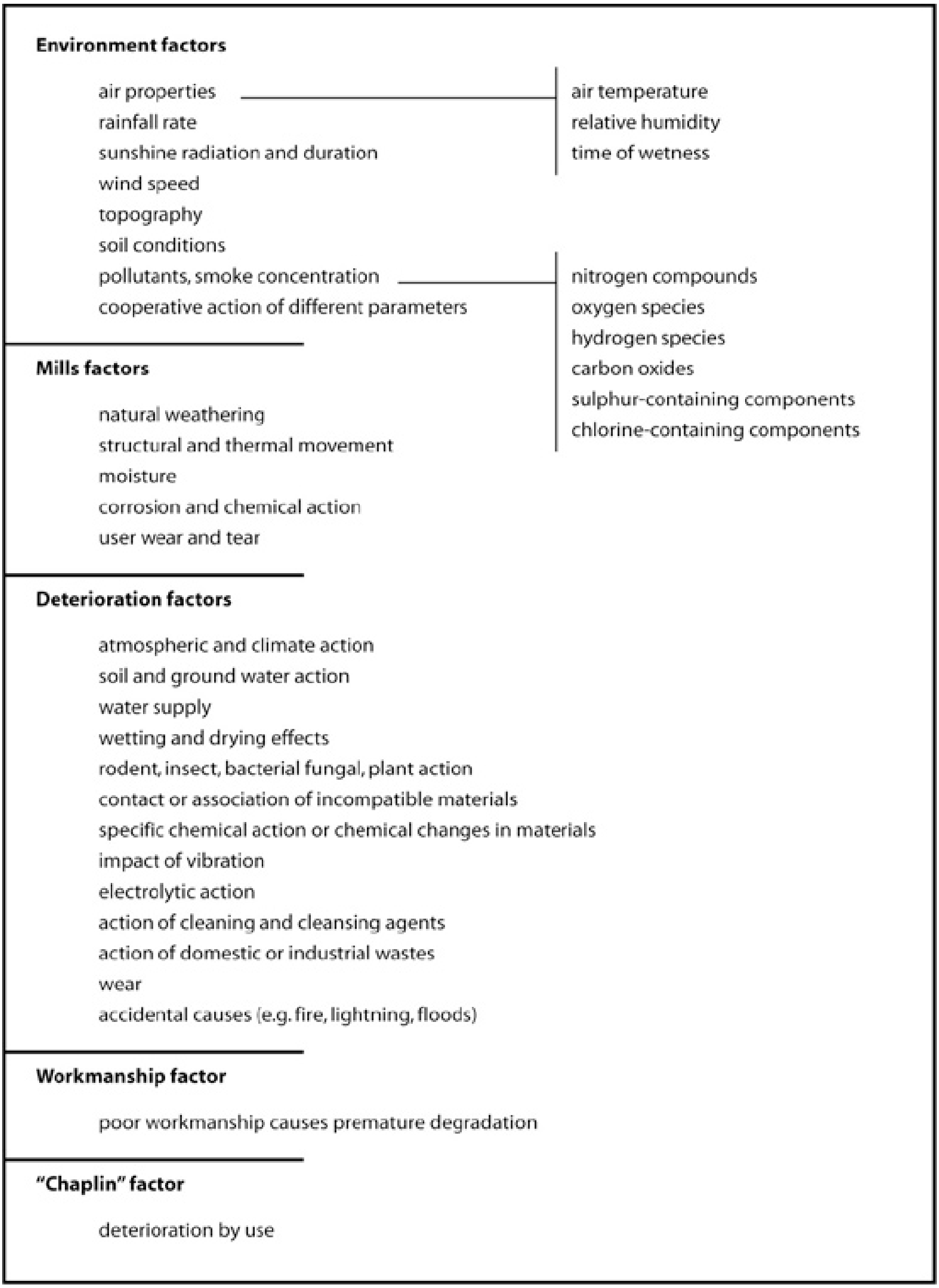
George Wypich's dream summarizes some of the multiple factors of weathering. If any theoretical solution exists, the literature on weathering materials and weathering effects has an increasingly range of books and articles, identifying building defects and searching the causes. These studies focus on the building degradation, comparing similarities in different cases to conclude with common defects. They do not aim to extend the building life but rather avoid premature degradations [02]. *"Scientific observation shows that some deteriorate at a faster rate than others depending on a set of controlling conditions or causal factors."*

According to the studies from Simpson and Horrobin [02], and Wypich [06], weathering factors can be classified in different categories as listed on figure 20.

From this board one can observe that weathering factors are various and numerous. They may play a role in different cases producing different effects; likewise the combination of two factors can create a new weathering factor, which increases the list and complicate the formulation of results (e.g. the combination of the air temperature and the rainfall rate produces the frost attack).

Simulating all these effects would take years or even is impossible. Considering that some of them affect the building more than others, we concentrate on the significant factors listed in the next paragraph and leave the minor factors out of the simulation.

Finally our main lack is the time definition for the simulation.



Environment factors

air properties
rainfall rate
sunshine radiation and duration
wind speed
topography
soil conditions
pollutants, smoke concentration
cooperative action of different parameters

air temperature
relative humidity
time of wetness

nitrogen compounds
oxygen species
hydrogen species
carbon oxides
sulphur-containing components
chlorine-containing components

Mills factors

natural weathering
structural and thermal movement
moisture
corrosion and chemical action
user wear and tear

Deterioration factors

atmospheric and climate action
soil and ground water action
water supply
wetting and drying effects
rodent, insect, bacterial fungal, plant action
contact or association of incompatible materials
specific chemical action or chemical changes in materials
impact of vibration
electrolytic action
action of cleaning and cleansing agents
action of domestic or industrial wastes
wear
accidental causes (e.g. fire, lightning, floods)

Workmanship factor

poor workmanship causes premature degradation

"Chaplin" factor

deterioration by use

Figure 20: identifying categories of weathering factors

The wide range of building defects has listed the common degradations, but rarely information about the time is mentioned. That is because a theoretical situation about weathering probably does not exist, and apart from the factors above, the influence of the weathering effects depends on the orientation, surface geometry, sectional geometry, position and design details of the object [02].

Apart from the theory, another start point for the simulation is the site-observation on real and existing buildings. Even if no generalization can be made from a single example, it brings support and reference for the simulation (e.g. getting the pattern or shape made by weathering effects). Weathered buildings are everywhere, and a close look at them can reveal much information for the results.

Selected weathering factors causing weathering effects

The main weathering factors are the environment factors, so they will take a large part in the simulation and they can not be omitted as mentioned by Wypich: “Experimental studies have told us that we need to know the weather conditions for a particular place or a particular experiment. Weather in a particular geographic location has a unique set of conditions which are difficult to reproduce exactly in any research set up. The exact weather data for a given geographic location are very important to relate weathering rates of laboratory equipment to the actual weathering rates.” [06]

Although these parameters are ever changing with the location, they first require much data from different locations, but once integrated into the simulation, one can compare results from these different locations.

A perfect weathering simulation would take into account the whole list of parameters above. In this approach based on concrete material, we selected the essential parameters which have the most influence. The figure links the selected weathering parameters (left column) to the property they affect (right column). In the middle is the name of the degradation.

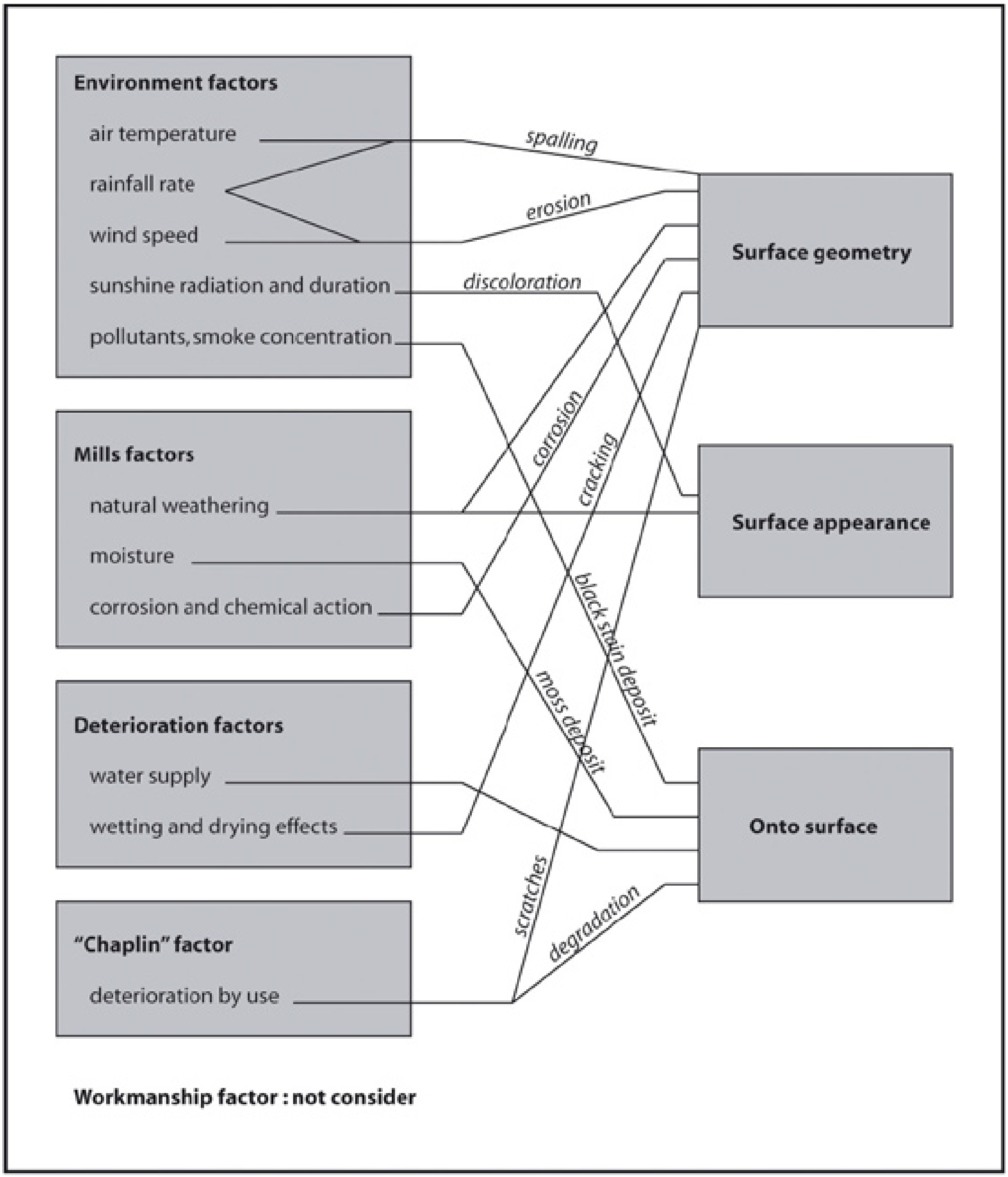


Figure 21: selected weathering factors and their effects on concrete

Proposed methodology to simulate weathering

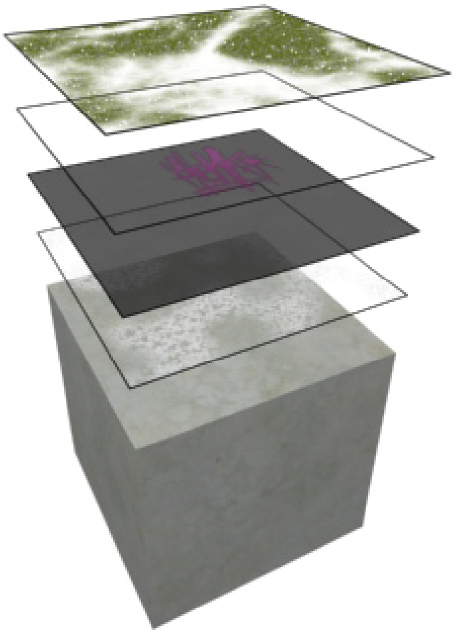


Figure 22: pile of layers in the simulation

Globally thinking, the research work aims at preparing the different factors for any posterior simulation. For this reason, each selected parameter listed above will be identified and integrated as a layer in the simulation figure 22), so it can be adjusted for any later simulation (e.g. environment factor depending on the location).

Some of the parameters will be saved in a 'start' scene, called environment scene, where one can import any 3D model and the others stored in the material directly.

The created material will be animated and time relative, which means that when a user changes the time setting, the applied material will change automatically according to the time. This complex material can be saved in a library as a single file, and then loaded on any computer. In the first step, we use the same technique as texture mapping, which is largely used in computer graphics, in which we add a time variation. We will present here the way how we created the aging concrete material: we took the example of a basic grey reinforced concrete, without any special internal or external treatment, made by standard workmanship. Following this method, one can create a different aging material and complete the material library. In a long range, the library will allow users to easily set up a weathering simulation on most of architectural buildings.

Because simulations are computational expensive, each of the parameters will be set up independently, based on small and virtual models. That way results are quickly rendered. In the final experiment of this work, all parameters and settings are used simultaneously.

Aging material: weathering simulation of the material

While creating a weathering material simulation, it is convenient to distinct deterioration in appearance (surface appearance) and deterioration in composition (surface geometry). Simpson and Horrobin [02] cleared this distinction as: *"Deterioration in appearance is associated with tonal and color changes of the external surfaces, either even or variegated, lighter or darker. The physical degradation or erosion of surfaces can cause changes in texture, as well as changes in shape or visual definition."*

Contrary to J. Dorsey and P. Harahan's work [07] on metallic patinas simulation, a weathering concrete simulation does not add effects to the surface but rather subtracts elements from it; erosion from both rain and wind is the main factor. A suitable representation of this subtraction consists of piling the different states of the concrete material in the time in different layers (figure 23), from top to bottom respectively, from the fresh concrete to aged concrete. While going in the time, the simulator will erase the first layer (new concrete) and show the second layer just below, and so on.

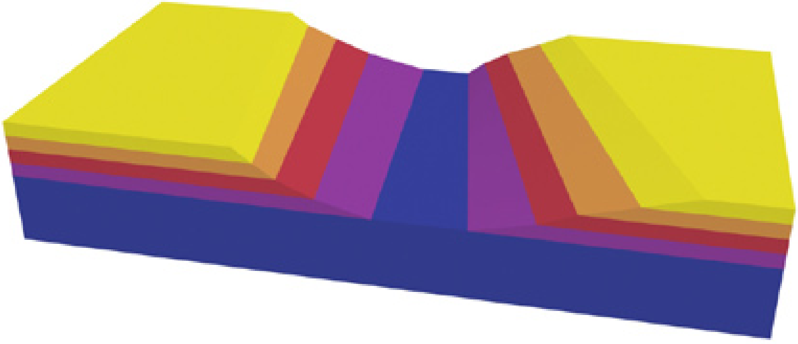
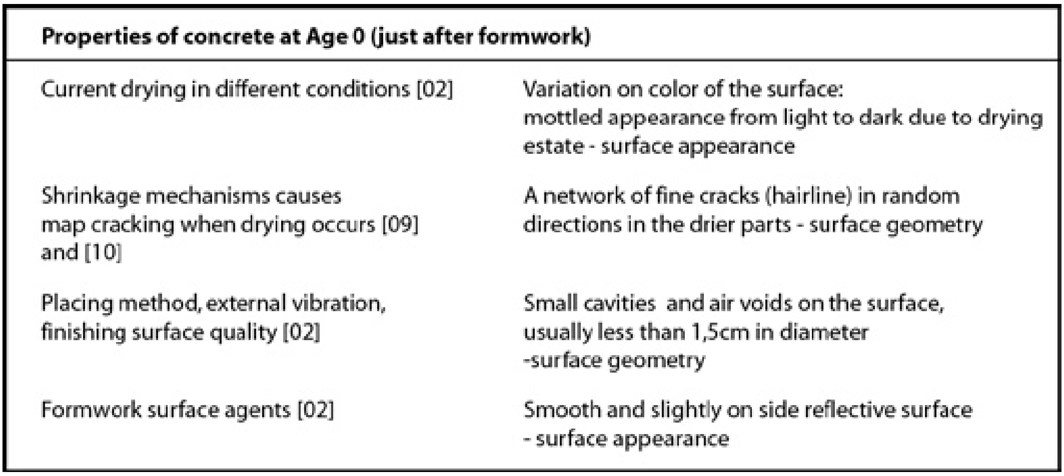


Figure 23: abstraction of the layered structure with erosion in the center

We have identified 5 key steps in the aging concrete, which provide differences on each step from one to another on both surface appearance and surface geometry.

We have called them in a range from Age 0 to Age 4, and have given an approximation on the time according to real examples observed.

Aging concrete Age O (appraisal 0 – 3 years old)



Properties of concrete at Age 0 (just after formwork)	
Current drying in different conditions [02]	Variation on color of the surface: mottled appearance from light to dark due to drying estate - surface appearance
Shrinkage mechanisms causes map cracking when drying occurs [09] and [10]	A network of fine cracks (hairline) in random directions in the drier parts - surface geometry
Placing method, external vibration, finishing surface quality [02]	Small cavities and air voids on the surface, usually less than 1,5cm in diameter -surface geometry
Formwork surface agents [02]	Smooth and slightly on side reflective surface - surface appearance

Figure 24: description of the factors and the concrete appearance at Age 0

Except for the case of an intended flat-finished surface, concrete always has small air voids on the surface, as well as short cracks from shrinkage. Different colorations of concrete can be obtained depending on the cement and the sand used.

Figure 25: schema of the surface geometry

Figure 26: example of texture Trappenzaal, Vertigo TU/e Personal photography

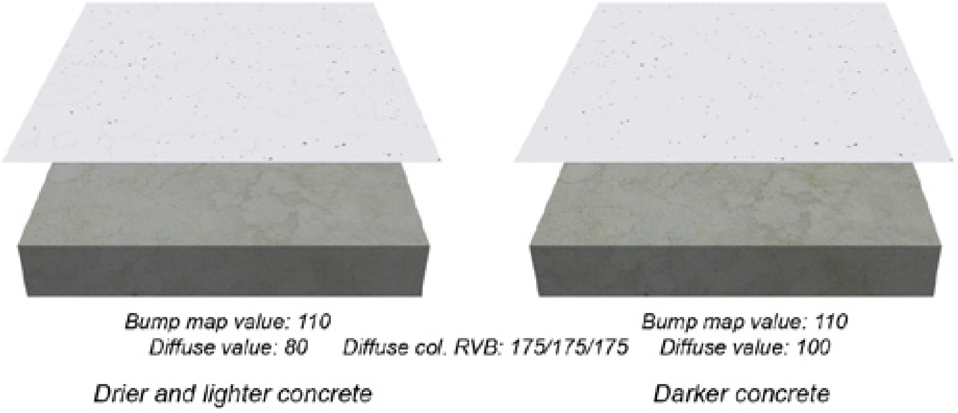


Figure 27: modelling the material description

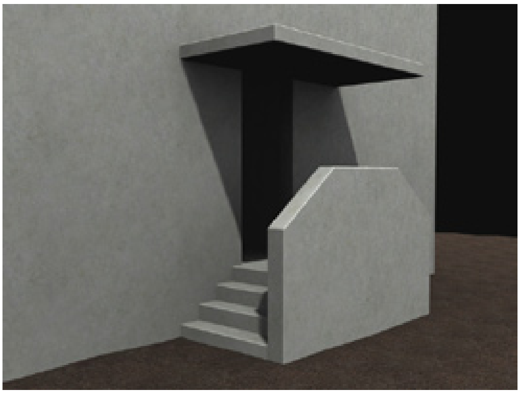
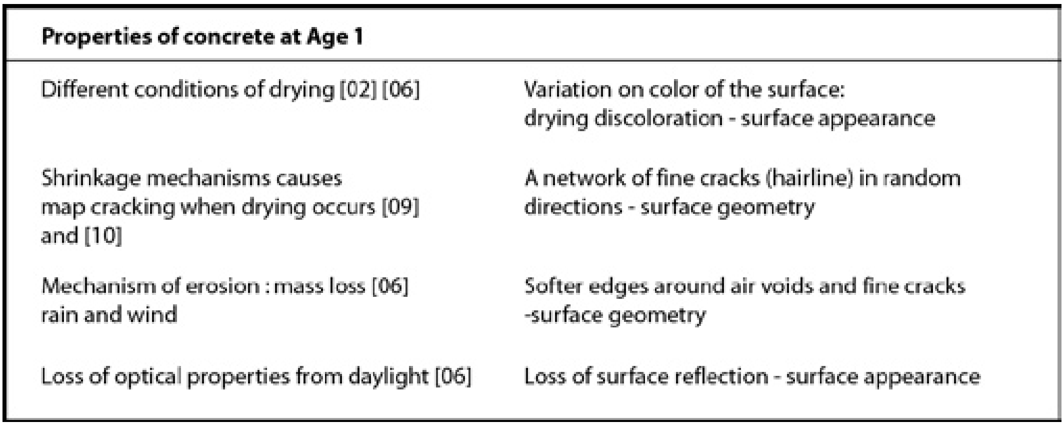


Figure 28: simulated result Age 0

Figure 29: simulated result Age 0 (detail)

Aging concrete Age 1 (appraisal 1 – 10 years old)



Properties of concrete at Age 1	
Different conditions of drying [02] [06]	Variation on color of the surface: drying discoloration - surface appearance
Shrinkage mechanisms causes map cracking when drying occurs [09] and [10]	A network of fine cracks (hairline) in random directions - surface geometry
Mechanism of erosion : mass loss [06] rain and wind	Softer edges around air voids and fine cracks -surface geometry
Loss of optical properties from daylight [06]	Loss of surface reflection - surface appearance

Figure 30: description of the factors and the concrete appearance at Age 1

Since most of the concrete material is already dried, the mottled appearance of tones is merging, and fine cracks are shown on the entire surface. Sharp edges around air voids are the first parts subjected to erosion, they become softer and leave more light into the air voids, and this results in a less deep optical effect.

Figure 31: schema of the surface geometry

Figure 32: example of texture
Haal, Vertigo TU/e
Personal photography

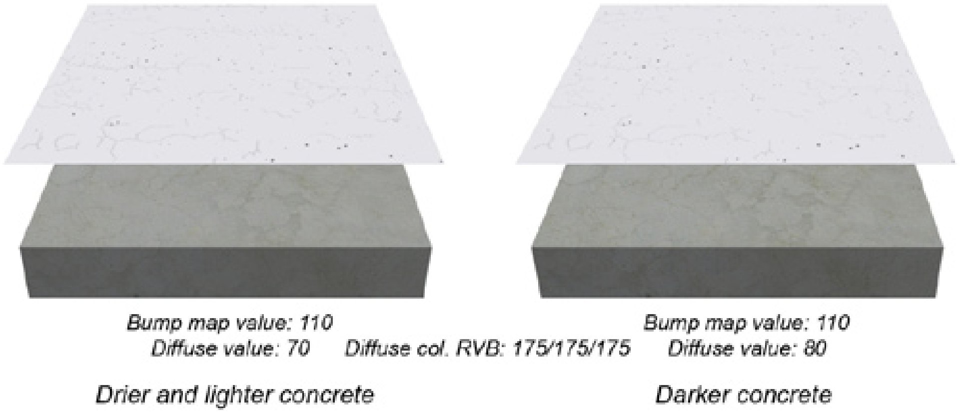


Figure 33: modelling the material description

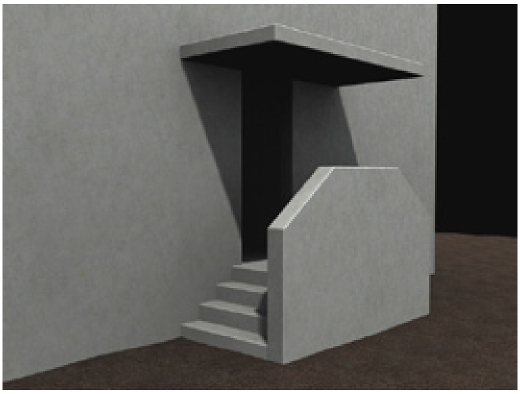
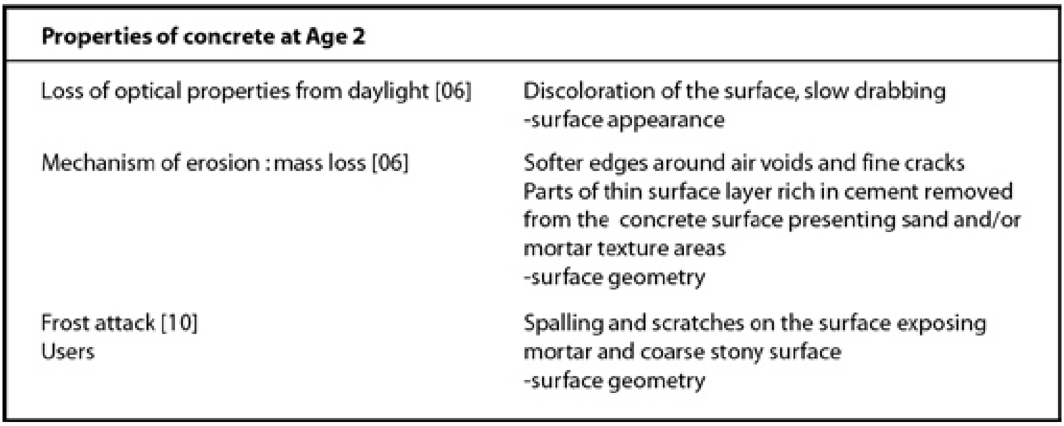


Figure 34: simulated result Age 1

Figure 35: simulated result Age 1 (detail)

Aging concrete Age 2 (appraisal 5 – 40 years old)



Properties of concrete at Age 2	
Loss of optical properties from daylight [06]	Discoloration of the surface, slow drabbing -surface appearance
Mechanism of erosion : mass loss [06]	Softer edges around air voids and fine cracks Parts of thin surface layer rich in cement removed from the concrete surface presenting sand and/or mortar texture areas -surface geometry
Frost attack [10] Users	Spalling and scratches on the surface exposing mortar and coarse stony surface -surface geometry

Figure 36: description of the factors and the concrete appearance at Age 2

The mechanism of erosion started to be visible and causes a slightly grainy surface, while air voids and cracks are vanishing. Some scratches from users or spalling from local defaults show the internal concrete material.

Figure 37: schema of the surface geometry

Figure 38: example of texture
Hoofdgebouw TU/e
Personal photography

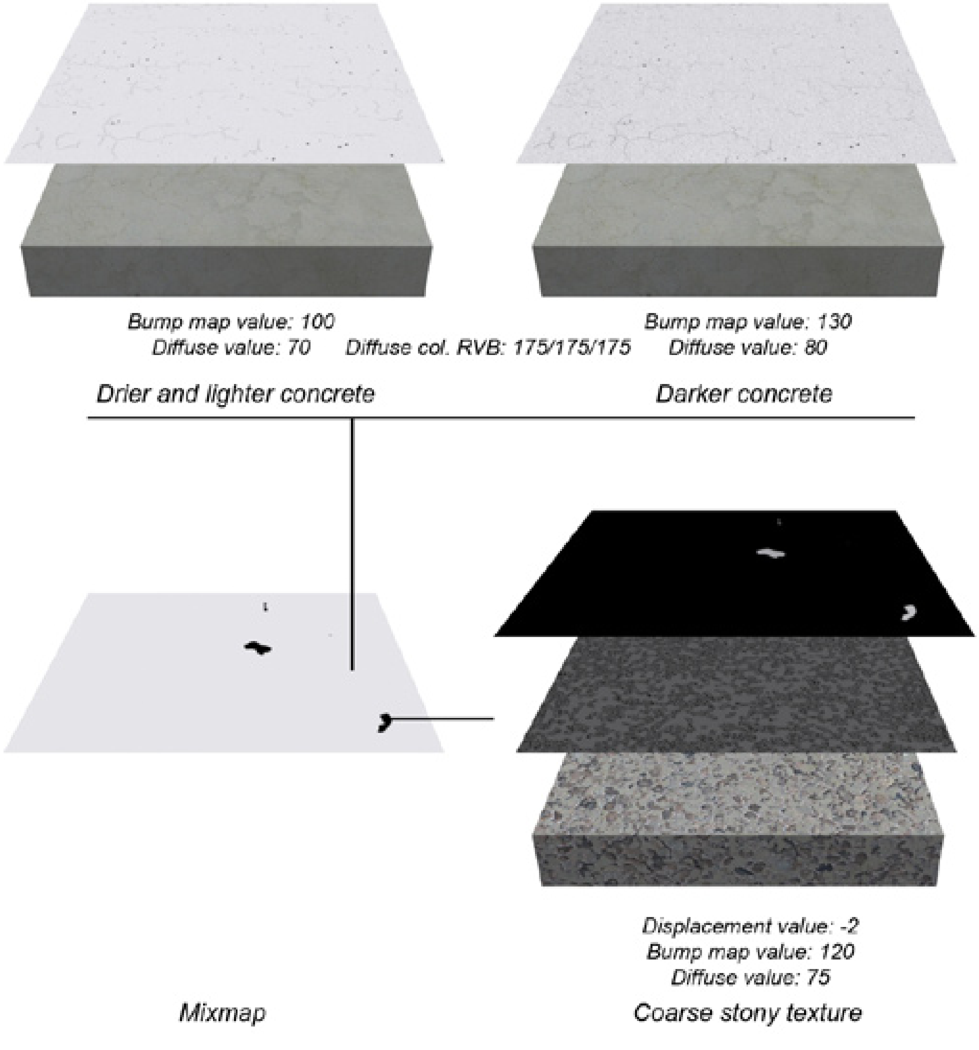


Figure 39: modelling the material description

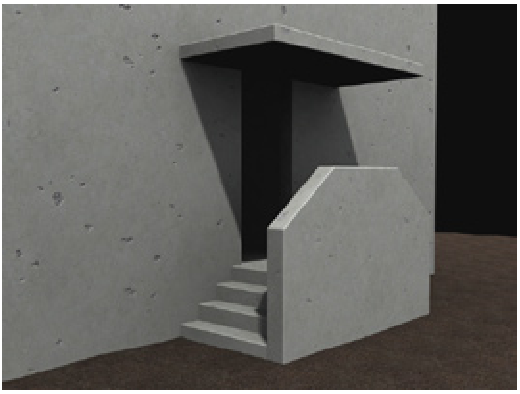
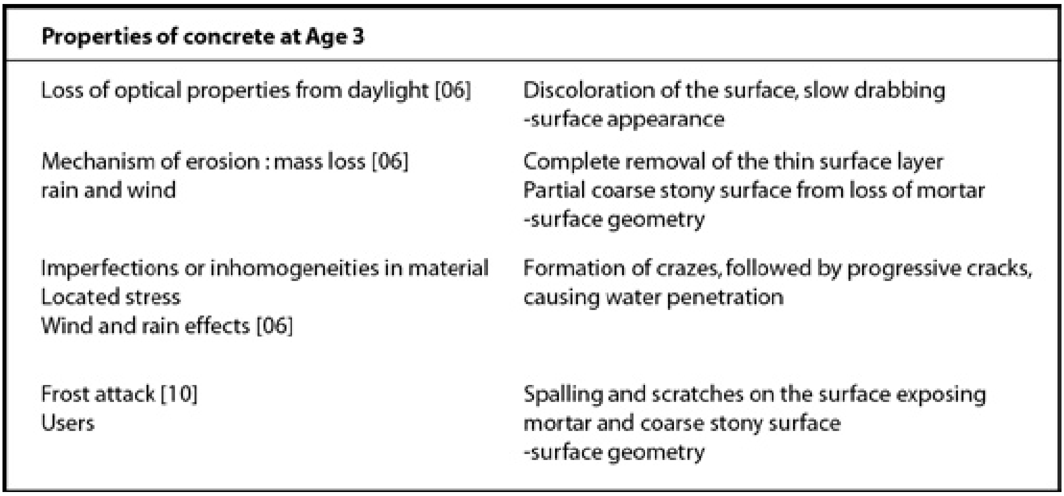


Figure 40: simulated result Age 2


Figure 41: simulated result Age 2 (detail)

Aging concrete Age 3 (appraisal 20 – 70 years old)



Properties of concrete at Age 3	
Loss of optical properties from daylight [06]	Discoloration of the surface, slow drabbing -surface appearance
Mechanism of erosion : mass loss [06] rain and wind	Complete removal of the thin surface layer Partial coarse stony surface from loss of mortar -surface geometry
Imperfections or inhomogeneities in material Located stress Wind and rain effects [06]	Formation of crazes, followed by progressive cracks, causing water penetration
Frost attack [10] Users	Spalling and scratches on the surface exposing mortar and coarse stony surface -surface geometry

Figure 42: description of the factors and the concrete appearance at Age 3

The mechanism of erosion spread on all the surface, and coarse texture appeared at the most eroded places. We assume that from this time severe cracks are appearing, those will later alter the building strongly.


Figure 43: schema of the surface geometry


Figure 44: example of texture
De Bunker, TU/e
Personal photography

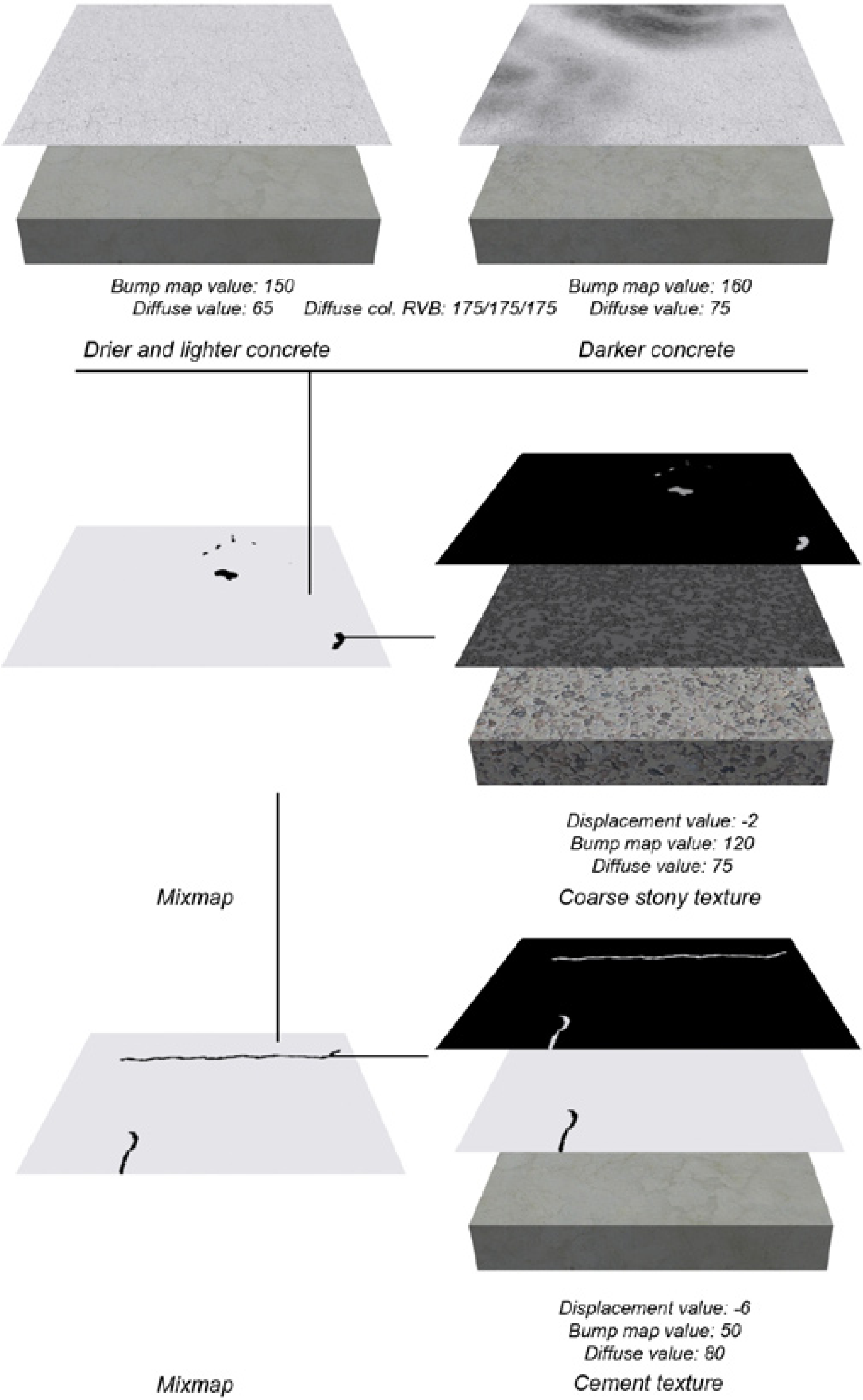


Figure 45: modelling the material description

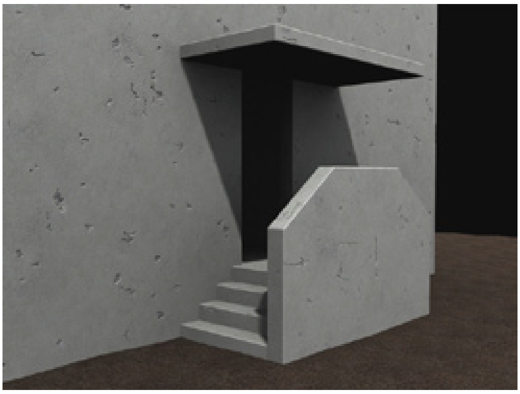


Figure 46: simulated result Age 3


Figure 47: simulated result Age 3 (detail)

Aging concrete Age 4 (appraisal 40 – 120 years old)

Properties of concrete at Age 4	
Loss of optical properties from daylight [06]	Discoloration of the surface, slow drabbing -surface appearance
Mechanism of erosion : mass loss [06] rain and wind	Widespread of the coarse stony surface -surface geometry
Corrosion of metal reinforcement due to water penetration, frost attack [09]	Spalling of external face -surface geometry
Frost attack [10] Users	Spalling and scratches on the surface exposing mortar and coarse stony surface -surface geometry

Figure 48: description of the factors and the concrete appearance at Age 4

Representing the end of the simulation, the surface of the concrete is really eroded and shows a coarse texture on most of the area. More scratches appeared to cause a rough surface, while pieces were removed from the surface after water penetration; the metal reinforcement is visible and is affected by a severe corrosion.


Figure 49: schema of the surface geometry


Figure 50: example of texture
De Bunker, TU/e
Personal photography

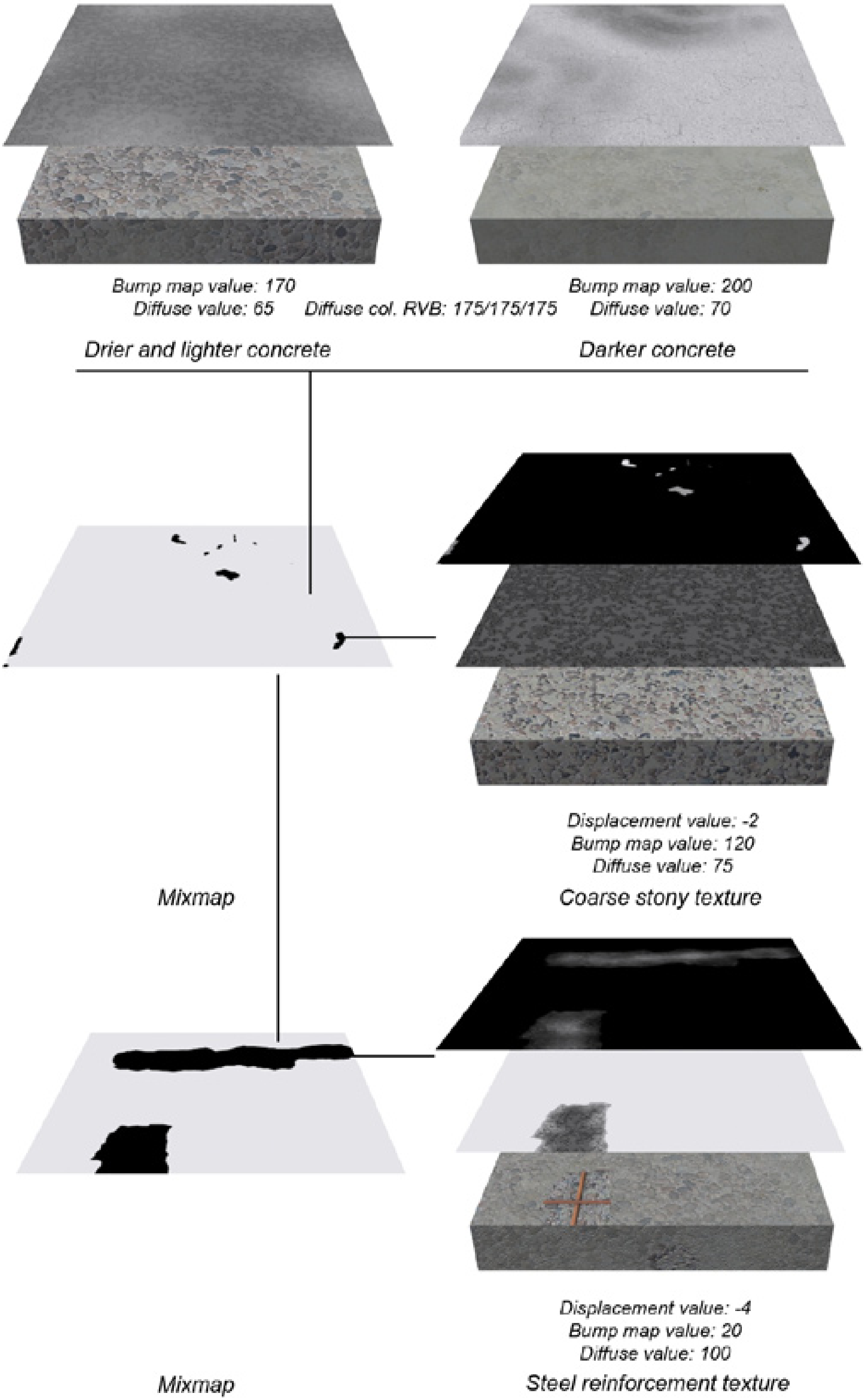


Figure 51: modelling the material description

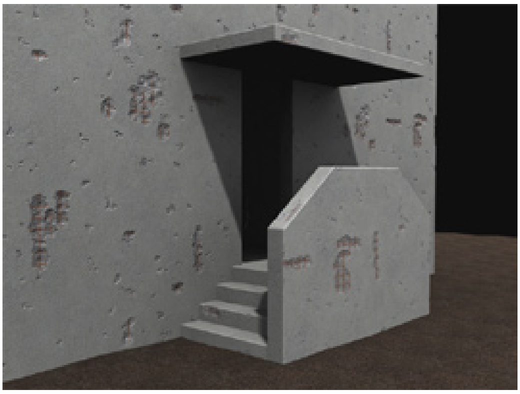


Figure 52: simulated result Age 4


Figure 53: simulated result Age 4 (detail)

The organization of the concrete material Age 4 follows exactly the Age 3 one to get a progressive and synchronized transition between the scratches, the cracks and the spalling when animating the material.

Although the different maps used for this simulation have different real distance scales to generate random, the technique we applied keeps being texture mapping; all faces are weathering at the same rate, and the position of scratches and spallings are not defined by the object geometry but according to the mapping. In reality the exposed rate of a surface determines its weathering rate, and protected surfaces hardly do weather.

To fulfill this lack, we have to continue with an advanced simulation in which the two main factors involving weathering are considered: rain and wind. In our approach we used particles representing raindrops.

Advanced aging simulation: creating the weathering maps

The weathering map will be the first created element in any further simulation, in the first step called ‘first pass’. Thousands of particles will be emitted into the scene and perhaps impact the object of the simulation. Each impact will be represented as a mark on the object. Each mark runs weathering effects.

Rainfall rate and wind speed, the main factors of weathering on materials, are data that can be collected from meteorological stations (figures 54 and 55). Because we can not simulate each drop from the rain, we will assign the average rainfall to a certain amount that can be adjusted

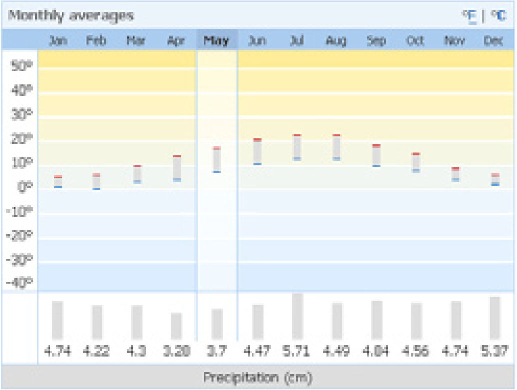
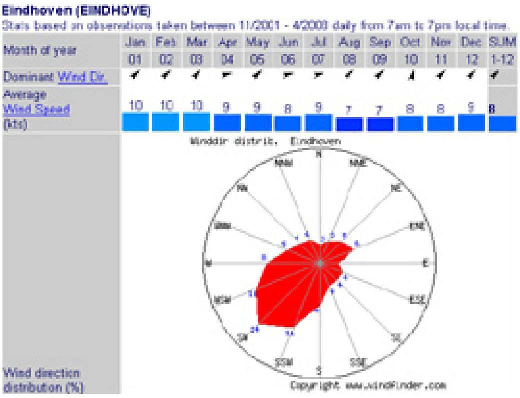


Figure 54: average rainfall rate from Eindhoven meteroligical station
Source: http://weather.msn.com



Eindhoven (EINDHOVE)
Stats based on observations taken between 11/2001 - 4/2008 daily from 7am to 7pm local time.

Month of year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	SUM
	01	02	03	04	05	06	07	08	09	10	11	12	1-12
Average Wind Speed (kts)	10	10	10	9	9	8	9	7	7	8	8	9	8

Figure 55: wind speed directions from Eindhoven meteoroligical station
Source: http://www.windfinder.com

if compared to different locations. Wind direction will affect the place where particles will stick; protected surfaces from main wind direction will get fewer particles than fully exposed surfaces.

To get a clear visualization of the raindrops paths under the effect of wind in the scene, we will use a sample model: few walls oriented in different directions and a roof which provides protected areas (figure 56).

Following the schematic view of the scene, particles are emitted from a virtual plane above the target object, in random directions and divergence. Under a gravity force, they are pushed within the four wind directions, whose have strength coefficient according to the wind map, and a turbulence coefficient. When a particle hits the object surface, it will be rendered as a mark at this point. If a particle hits the ground, it is removed from the simulation for performance gains.

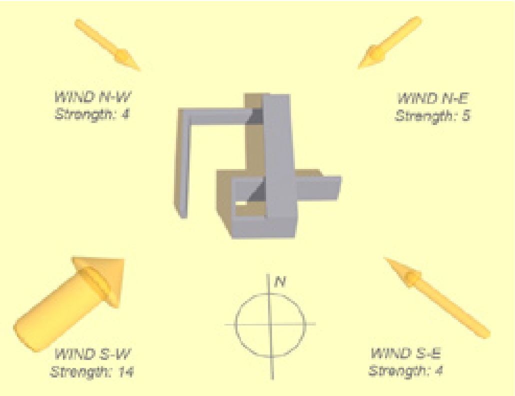


Figure 56: schematic view of the wind effect modelled in the simulation

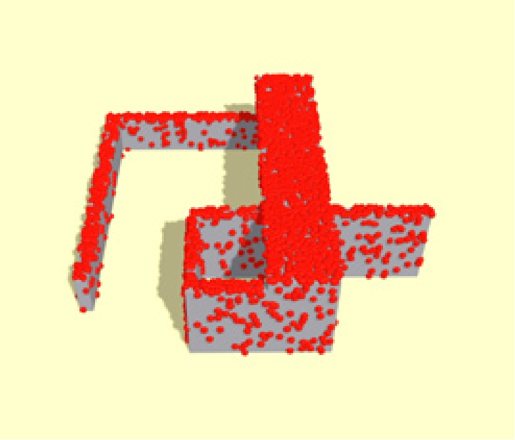


Figure 57: example of rendered particles onto surfaces

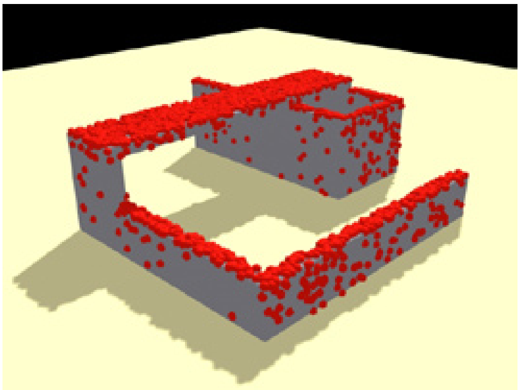


Figure 58: different rates of particles on exposed/unexposed surfaces

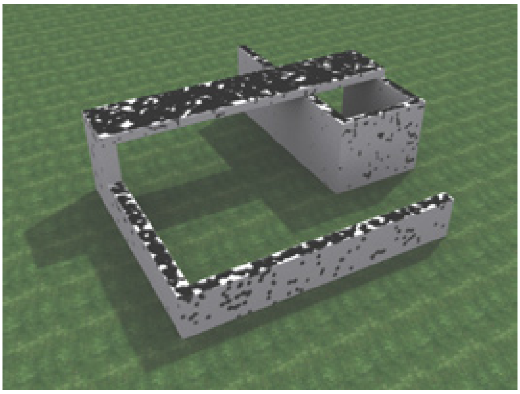


Figure 59: applying the weathering map to the object

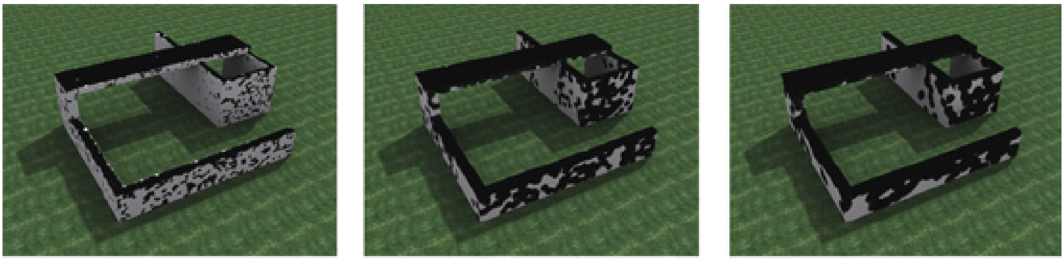
On a different view, one can observe differences of impacts between exposed and protected surfaces (figure 58). Later, the weathering map is applied to the object: the black spots represent the weathered points, and white surfaces are not affected by weathering.

The compass, ground, wind force, gravity force, and particle source are referred to the location of Eindhoven. These settings can be reused for any simulation in Eindhoven; the scene can be shared and other locations can complete these start settings.

♦ Setting the rainfall rate into particle amount:

Since weathering takes place during years and our simulation can not consider the number of raindrops, the amount of particles being emitted into the scene might be determined by experimentation: we fixed this amount when exposed surfaces are mostly covered by particles. Every particle is rendered as a sphere; a falloff is applied to the sphere so it goes gradually from a full opaque center to a transparent rounded border. The results depend on two factors, the amount of thrown particles in the scene, and the size of the rendered particles. Throwing a huge amount of small particles will give an accurate result with advanced shapes but consumes computer resources. In contrast a small amount will render much quicker but shows the round shape of the particles in many places (figure 60).

This black and white weathering map mixes two aging materials in the simulation: at age 1, white surfaces will be rendered with the material age 0 and black surfaces rendered with the material age 1. Grey color will



Rate: 3000 particles/m²	Rate: 1500 particles/m²	Rate: 750 particles/m²
Particle size: 0,10m	Particle size: 0,20m	Particle size: 0,30m
Rendering time: 25 min	Rendering time: 18 min	Rendering time: 14 min

Figure 60: description of the factors and the concrete appearance at Age 4

blend these two materials depending on the darkness of it.

Creating only one weathering map can not be sufficient in our simulation: a single map defines the mixing position between two consecutive material ages (e.g. from age 0 to age 1). If we introduce a third material age in the simulation, using a single weathering map will result in the absence of the in-between material age: rendering a simulation at age 2 will place material age 2 on weathered surfaces and material age 0 on unexposed surfaces, with skipping material age 1 because one bi-color map can not be used to represent three different ages.

Figure 61 presents which weathering map we use between material ages when simulating further in the time: the next step will add a weathering map and an aging material layer following this scheam, and so on.

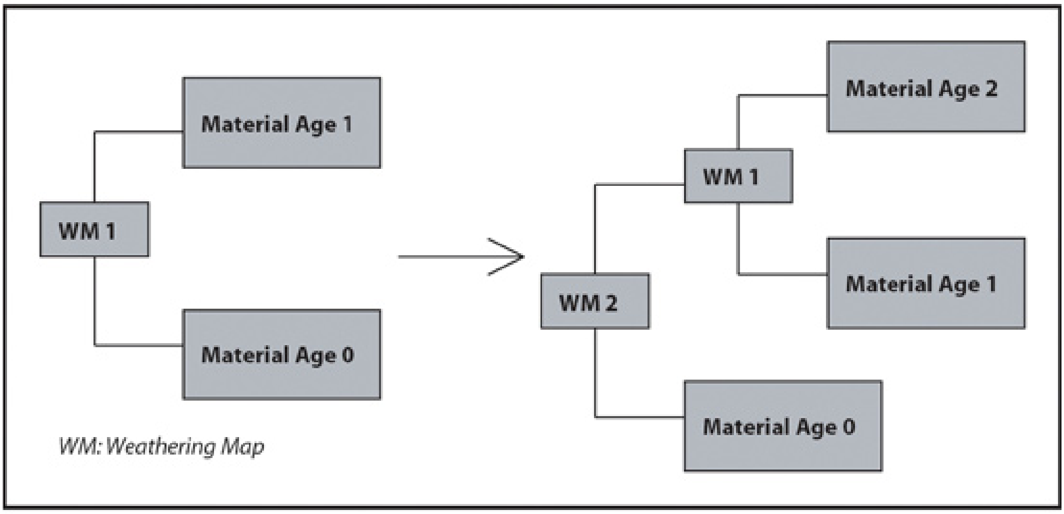


Figure 61: schematic view of the organization between material ages and weathering map when going in the time in the simulation

During the weathering process, degradation is spreading on surfaces. Our first weathering map generates the position of the main impacts. A second weathering map is created by throwing more particles, just like in reality; exposed surfaces will become fully covered by particles, the amount of particles on unexposed surfaces will increase, and protected places will keep being at the same state (figure 62).

In a nutshell, if we have identified 5 different ages in our simulation, we need 4 progressive weathering maps to provide an advanced simulation.

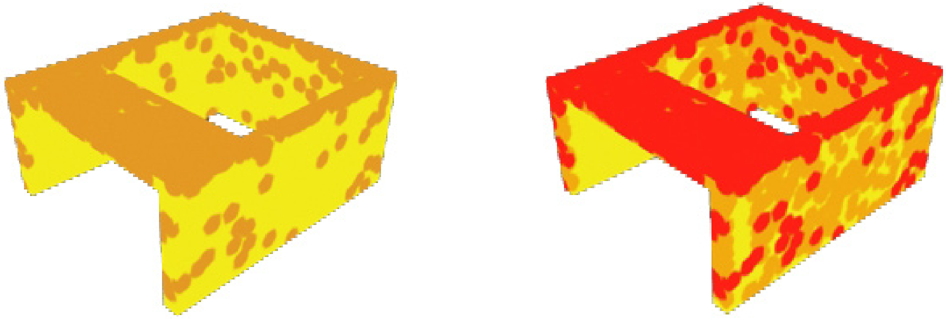


Figure 62: weathering map representation with schematic material colors. On the left, the first weathering map separates the first two material ages. On the right, two different weathering maps separate three material ages.

External weathering factors simulation : onto surface deposits

We called these factors external weathering factors since they do not modify the material directly, but change the appearance from their deposit onto the surface.

They are more or less common for every material and every simulation. We have identified four different factors to simulate: efflorescence, pollution, user degradation (particular case) and moss growth. All of them are represented as a layer in the material, but must not be rendered in every simulation: their effect is a single parameter that we can easily change manually (figure 63).

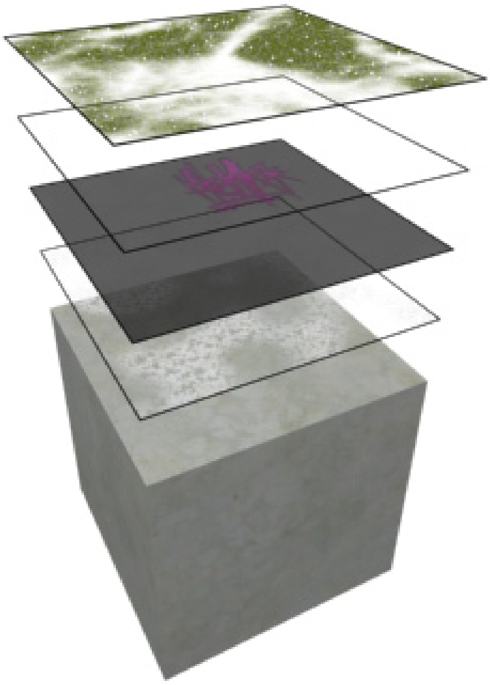


Figure 63: the different deposits layered in the simulation

♦ **Efflorescence**

Efflorescence is a common defect on porous materials such as concrete and brickworks. It is recognizable as a white powder or bloom onto the surfaces. Efflorescence appears when the building is drying out, salts are carried through or onto the surface by moisture, and when they crystallize they form a white or gray deposit [08].

Figure 64: a case of efflorescence on a concrete pavement
Source: www.concretenetwork.com

Figure 65: a case of indoor efflorescence
Source: www.activerain.com

Figure 66: a close view on efflorescence
Source: www.cuttingedgecurbing.com

The exact location was mentioned by Cook and Hinks *"Since the process requires water, the take-up of salts will be localized to areas of the material that are subjected to wetting. Stone, concrete and brickwork are usually affected. Where parts of the materials are dry and others are frequently wet, capillary forces will carry the solution into the drier material. This produces a difficulty in assessment of the situation, since the salts can be carried considerable distances before emerging at a location that merely represents a good drying area. As drying out of the moisture occurs the salts are either deposited in the pores or on the surface"* [10].

Our simulation will not be able to calculate the exact point where moisture is drying out but efflorescence will be included since it is a weathering defect. The white powder material will be represented as flecks on the surfaces.Efflorescence happens only once, and soon after construction [10] unless a construction default. It will be washed by rainfall, or slowly disappear during the building life, as represented in figure 67.

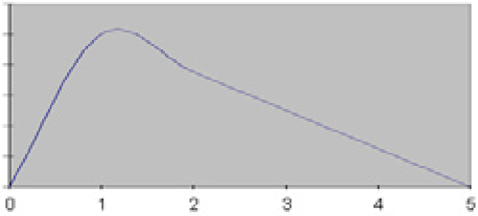


Figure 67: Schematic diagram of the presence of unwashed efflorescence along the building life

The presence of efflorescence on the surface will be filtered by the latest weathering map: rain washes efflorescence on exposed surfaces. In other cases it can be washed by cleaning but this is not considered in this simulation. If efflorescence is intentionally washed, we just don t render it.

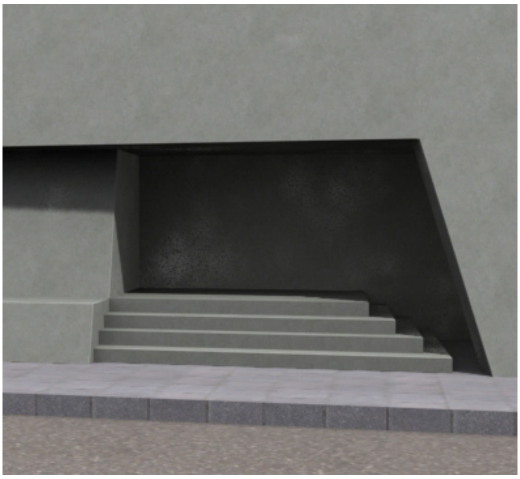


Figure 68: simulation of efflorescence visible only on protected surfaces

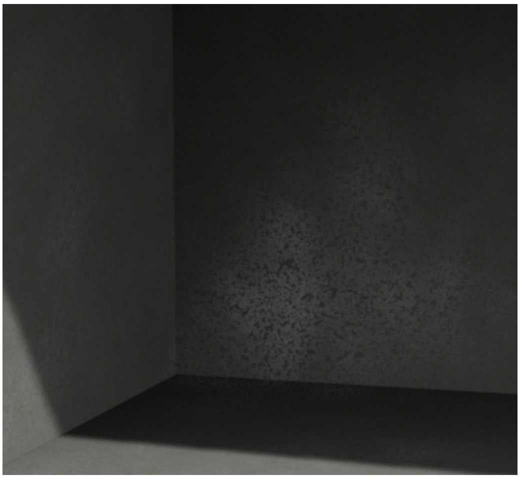


Figure 69: efflorescence, detail

♦ Dirt deposit from pollution

«The typically traditional urban problem is the disfigurement of buildings by pollution and dust.» [02]. Although defects from pollution are little known at present, it can literally change the facades of buildings. In city centers, black stained surfaces are common, due to high traffic. Basically pollution creates a black thin layer onto the surface, producing a darker appearance. The visual aspect changes are worse since this deposit can be washed by rain producing a non-uniform and highly-contrasted pattern: exposed areas keep the material appearance; all protected areas are suffering from pollution (figure 70). Therefore a complete cleaning of the façade is sometimes required, especially on historical buildings.

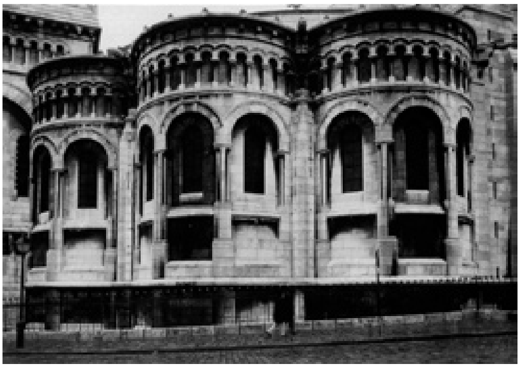


Figure 70: a typical example of pollution deposit on façade in city center

The atmospheric pollution makes actually more than a deposit onto the surface. Sulphurous acid and sulphuric acid are transported within the rain, and getting into the porous material surface [10]. This can result in an early disintegration of the stones. Since this reaction acts on exposed surfaces, we might neglect it in our simulation because we already simulated erosion on the concrete material; acid attacks are accelerating the process, and little data exist today to measure these rate in different locations.

Dirt pollution will be represented as a black layer onto the concrete material, and filtered by the weathering map, so it does not appear on exposed surfaces. The only parameter for this layer is its opacity; rarely a high polluted environment creates an opaque layer onto the surface, and the surface geometry is still visible through this layer.

The materials parameters are already set to increase in the time, from a transparent layer to the final value. The parameter required in the simulation is the rate of pollution in the environment; we fixed it from 0 to 100: a value of 0 means no dirt deposit that is almost unreal, a value of 100 represents a high polluted environment like a city center with high traffic in the neighborhood.

Figure 71: Different cases of dirt deposit simulation: on the left fresh construction with no pollution, in the middle a little-polluted environment (value: 15) and on the right a polluted environment (value 70)

♦ User's degradation: the case of graffiti

Not only environment degrades buildings, every day users are utilizing buildings and degrade it, of course at a small rate but after years some marks appear especially in crowded areas. This phenomenon is mostly in indoor rooms so apart of our work, moreover it requires a previous users' paths simulation to localize the impacts positions. The only users' degradation we will represent is the graffiti case, voluntary made by persons.

Figure 72: a traditional case of graffiti
Willemstraat, Eindhoven
Personnal photography

Since any graffiti can be repeated in reality and therefore in the simulation, its position must be set manually, and placed only once on the object. Actually, graffiti are manually hand made in reality too!

Our simulation contains three different kinds of graffiti, on independent layers; so it creates four levels of degradation, on level 0 there is no graffiti and on level 3 there are the three kinds of graffiti.

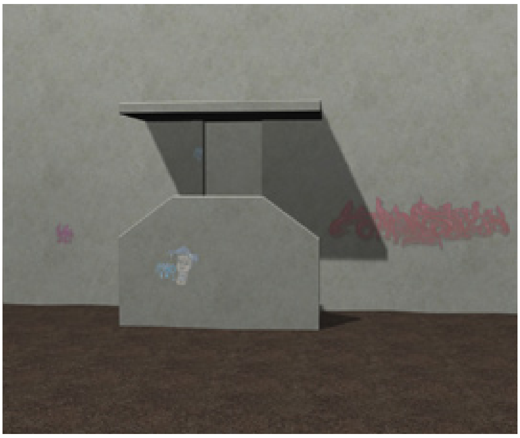


Figure 73: The maximum of 3 graffitis from the simulation painted on walls

Figure 74: detail on the painting

♦ Vegetation growth onto surfaces

As the last environmental factor of our simulation, vegetation growth is probably the most representative one from the surrounding events acting with the building surfaces. Under humidity conditions, vegetation can cover large parts of surfaces and change enormously the building appearance.

Although vegetation is a general term, many types of vegetation exist and they have their own conditions of localization, sunlight exposure and growth (e.g. Funghi, lichens, mosses) [02]. Here we will concentrate on the moss growth onto surfaces.

Moss formation can be found almost everywhere since the requirements are both water and sunlight effect [04]. Moss will appear quickly on any rough moist surface on which soil and dirt can collect; once established they tend to hold moisture in the supported surface [02].

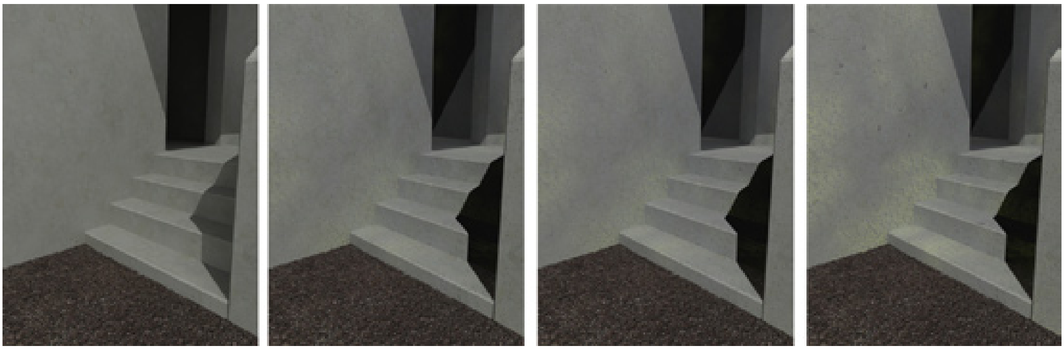


Figure 75: a sequence of moss growth onto surfaces

APPLICATION EXAMPLE ON A SCULPTURE ON THE TU/e CAMPUS

In this part we will present the procedure to follow in our weathering simulation on 3Ds Max. We will explain more in details the different practical stages and give some advices to reach better results.

Figure 75: view of the sculpture in its environment today

This sculpture is interesting for the final test of this research since it is entirely made in concrete, and built on the TU/e campus. Moreover an artistic form is developed providing different expositions on surfaces, bringing shadows and brightness. The object has been built at the human scale so it can be assimilated to an architectural object.

It was designed by two students from the TU/e: Verheijen, J. and Evenhuis, R. and the construction finished on November 2006.

Preparing the model and rendering the weathering maps

♦ **Preparing the object**

It is important to model details in the 3D object such as cornices, chamfer, and in general any relief on the surfaces. The simulation is geometry-dependent, so any detailed shape can give more accurate results and effects, which texture mapping does not.

In this case the object has many faces. We modelled it as an editable poly object. Since the weathering maps are size-limited, we divided the original object in three parts to later render weathering maps for each part and not for the whole object. Doing so we do not loose quality details and we keep undersized maps to get faster renderings. The inconvenience is that the model will contain some seams, so these seams should be placed at little visible positions.

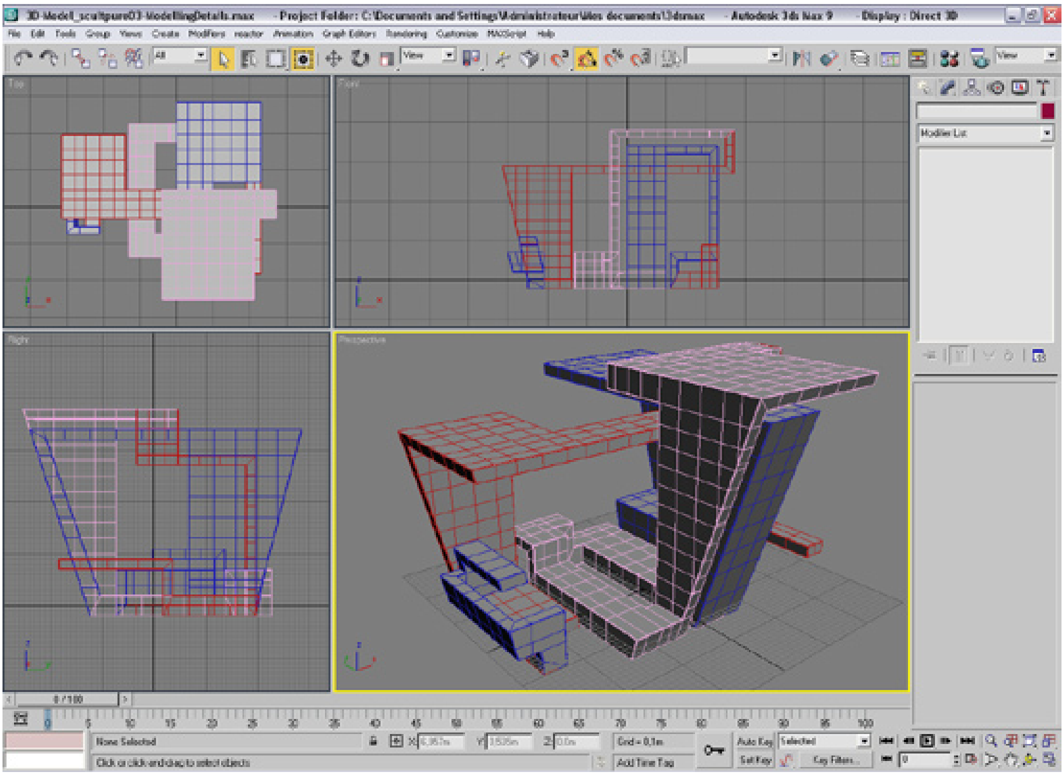


Figure 76: modelling details on the object and dividing it in three parts (red, pink and blue edges)

♦ Rendering the weathering maps

.Here we will describe the procedure to set up the scene and the particle emitter to render the weathering maps:

♦ open the start scene "Eindhoven" and merge the objects in the scene at the origin (0,0,0)

♦ orient the objects according to the compass above the scene

♦ make copies of the StopObjectdeflector present in the scene, as many as objects to weather

♦ link them to their respective object in the modify panel -> pick object (figure 77)

♦ the ground deflector is already linked to the ground object in the scene

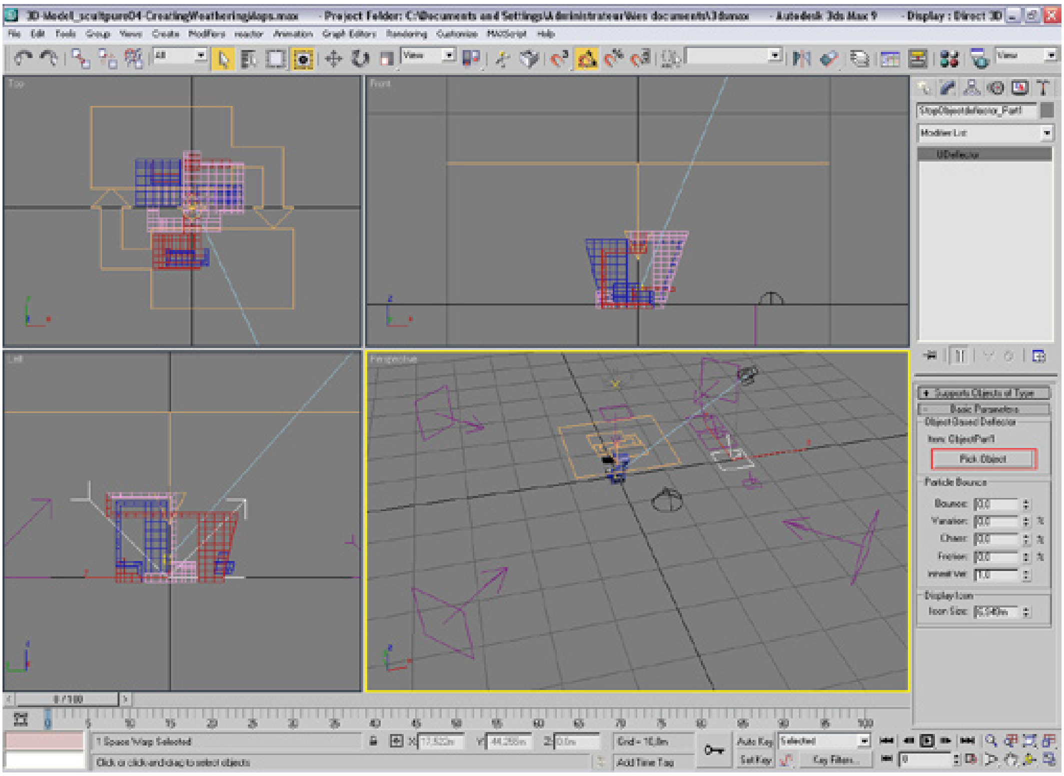


Figure 77: setting up the environment scene and applying the deflectors to the objects

♦ add them to the particle system: open the particle view, and select the collision01 event. Add all the StopObjectdeflectors to the collision01 (figure 78).

Now emitted particles will stop on the object and die on the ground object

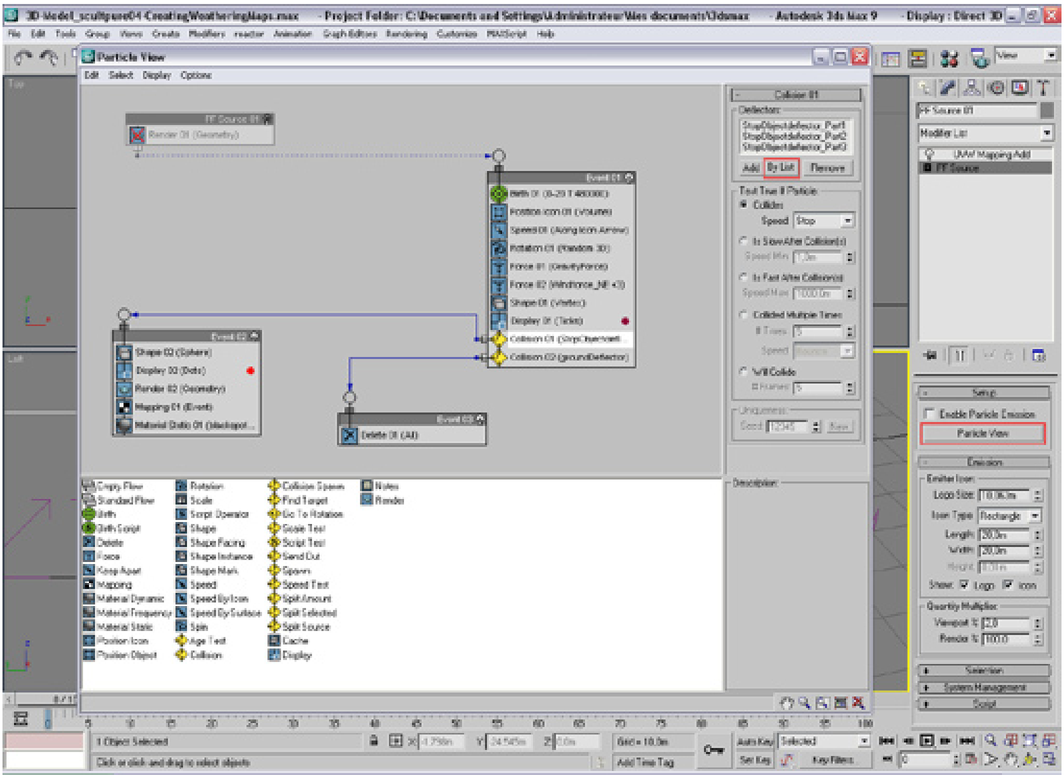


Figure 78: setting up the particle emitter for particles to stop on the object

To render the weathering maps we need to render the particles on a map corresponding to the surfaces of the object. But particles do not render using the *render to texture* tool. A solution to render the particles on the surfaces with render to texture is using their shadows. We will place as many lights as the object geometry requires around the object to light it completely, and render the geometry as a 2D unwrapped map of the object.

♦ add some lights to obtain a full white surface on the selected object to create its weathering map. Putting many lights will help (figure 79). The render to texture tool will work with the shadows from the particles to the surface, so we need lights in every direction to avoid unexpected shadows. We may make a test without throwing particles and render the map to see if all the surfaces are fully white and any shadow is rendered (figure 80). If we have some grey surfaces, we will add more lights at this place.

The other parts of the object will not be rendered, but transparent not to bring any shadow. They have to be present in the scene to stop particles.

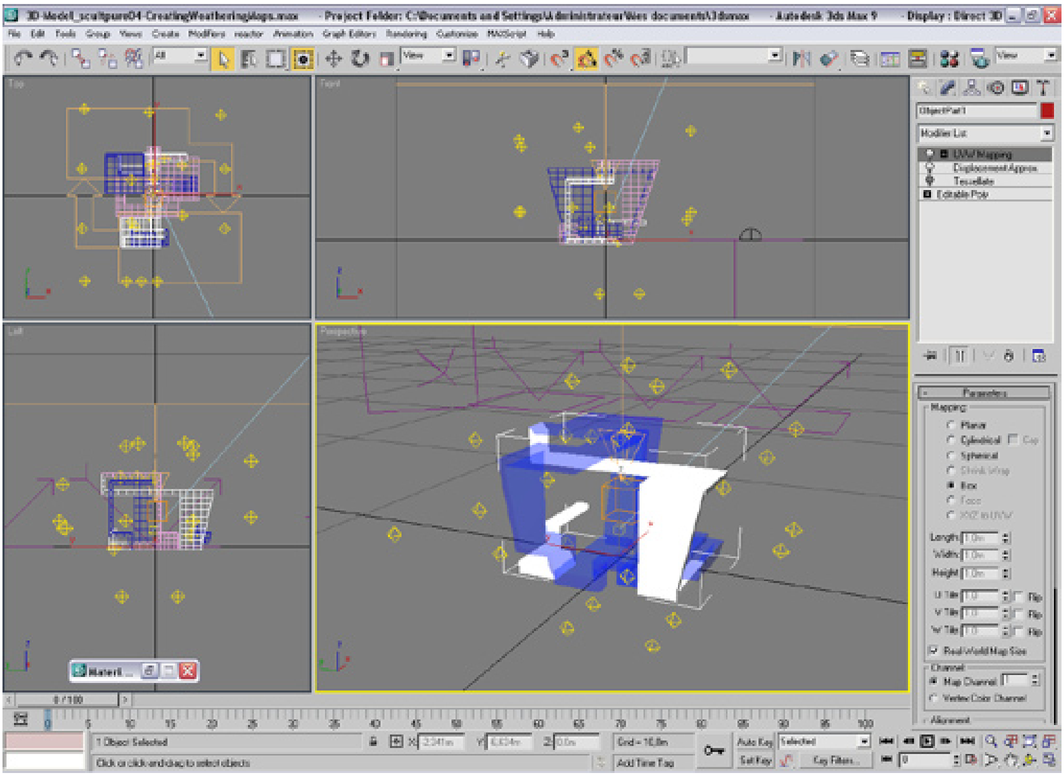


Figure 79: lighting the object to render the weathering maps

Figure 80: rendering the map without partciles to check if all surfaces are fully white

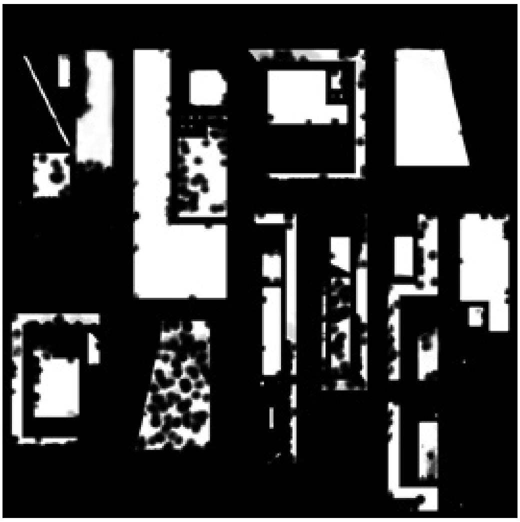
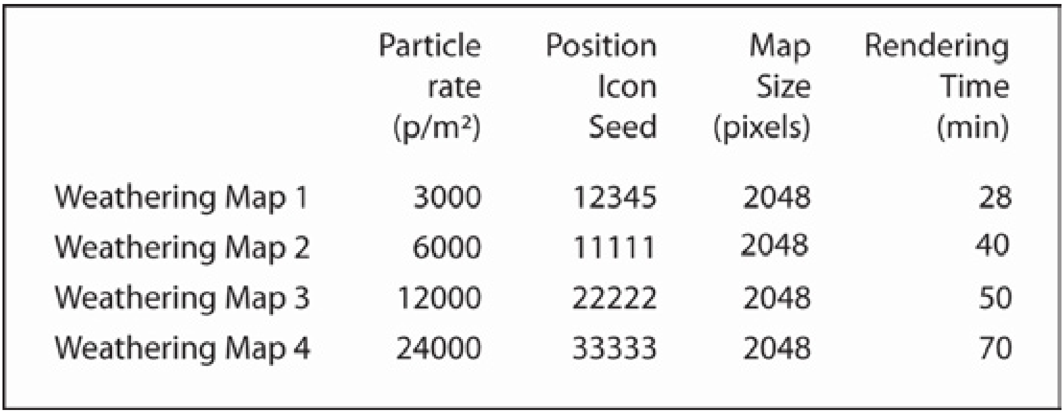


Figure 81: the weathering map 1 for the object part 1 of our model

We will reproduce this method for the three objects in the scene with specific lighting for each object. Then we will render all the weathering maps with the parameters described in figure 82 for the particle emitter.



	Particle rate (p/m²)	Position Icon Seed	Map Size (pixels)	Rendering Time (min)
Weathering Map 1	3000	12345	2048	28
Weathering Map 2	6000	11111	2048	40
Weathering Map 3	12000	22222	2048	50
Weathering Map 4	24000	33333	2048	70

Figure 82: settings and rendering time for this simulation

N.B: to render the weathering map 2 (WM2), we applied the WM 1 as a diffuse color to the object. So altered part in WM1 will be for sure altered in WM2, and so for the next weathering maps.

Creating the animated material

We will create the hierarchy for the animated material with

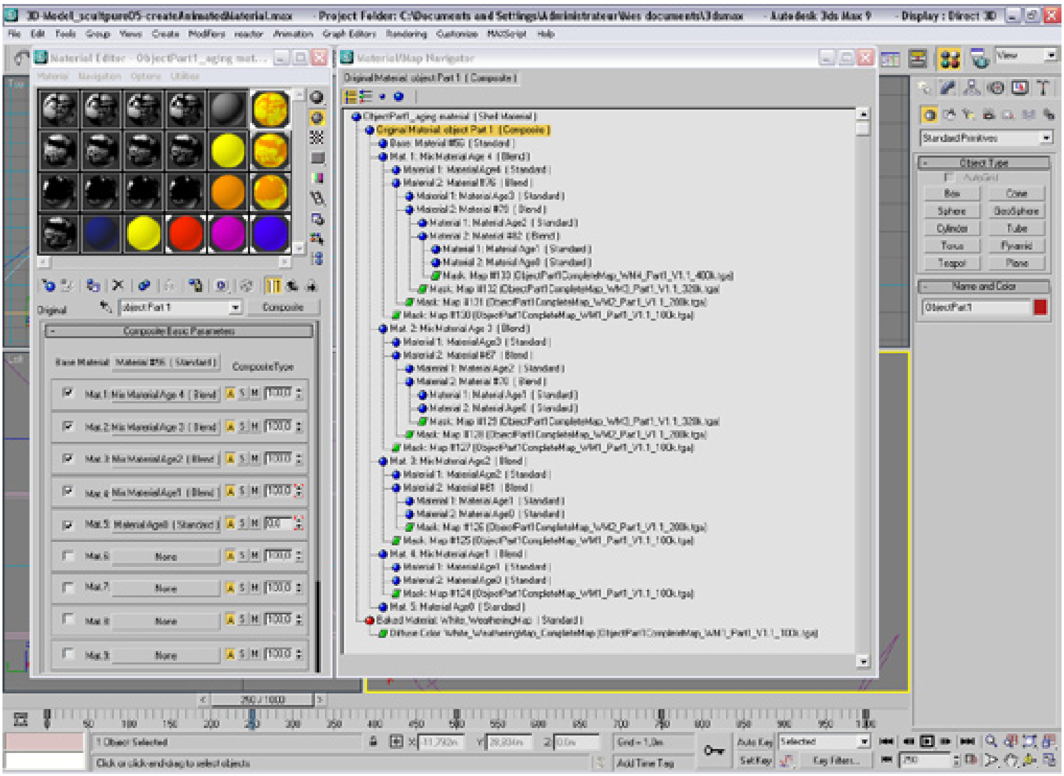
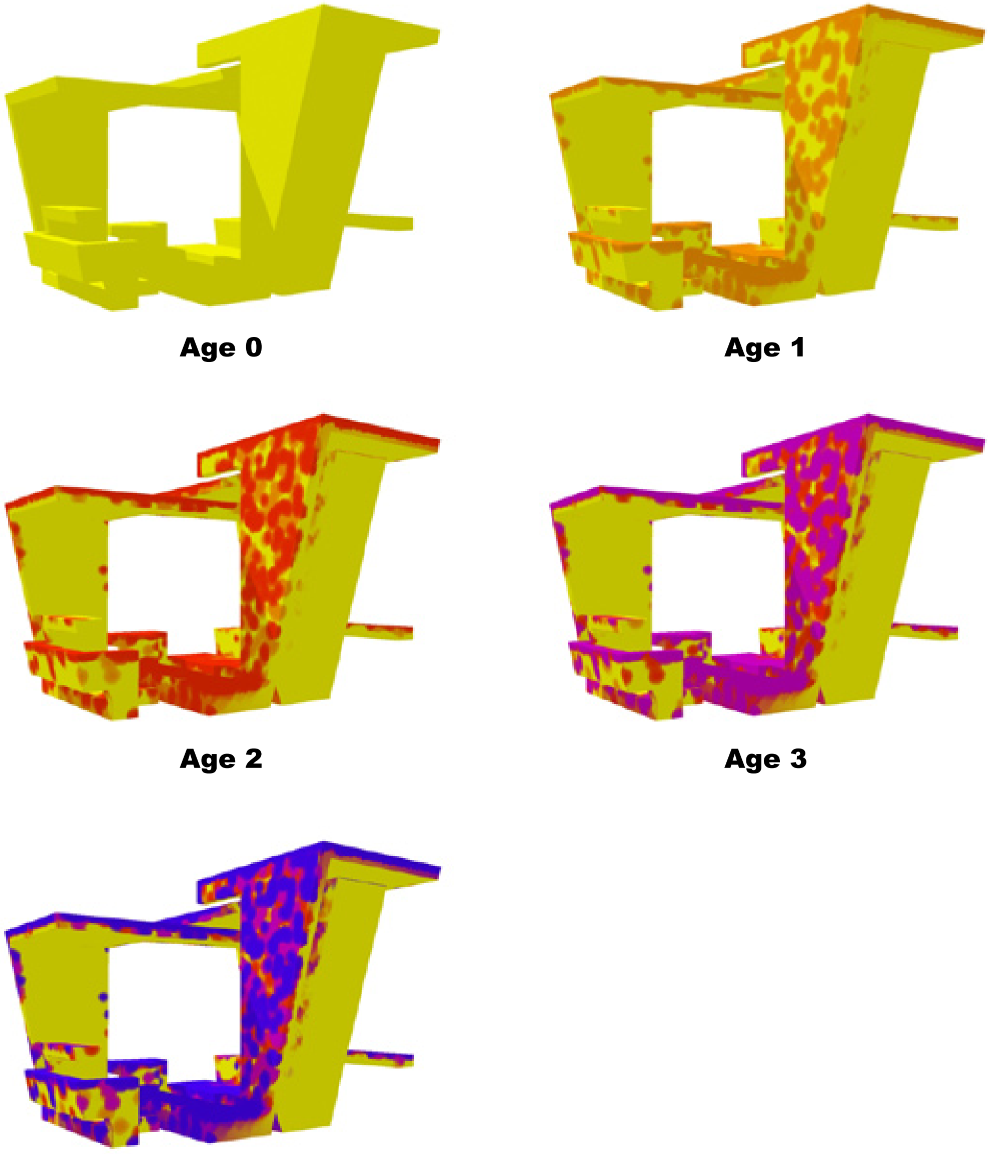


Figure 82: a composite material makes the hierarchy with material ages and weathering map. Some keyframes are placed to “erase” the different layers in the time

weathering maps and schematic colors. The complete material has five different ages, and in the time more weathering maps (from 1 to 4) will separate the different material ages (from 0 to 4) (figure 82). We use first schematic colors as materials to see clearly the difference between ages (figure 83), when the hierarchy is established, we will simply replace the schematic colors by the material ages from the library.



Age 0

Age 1

Age 2

Age 3

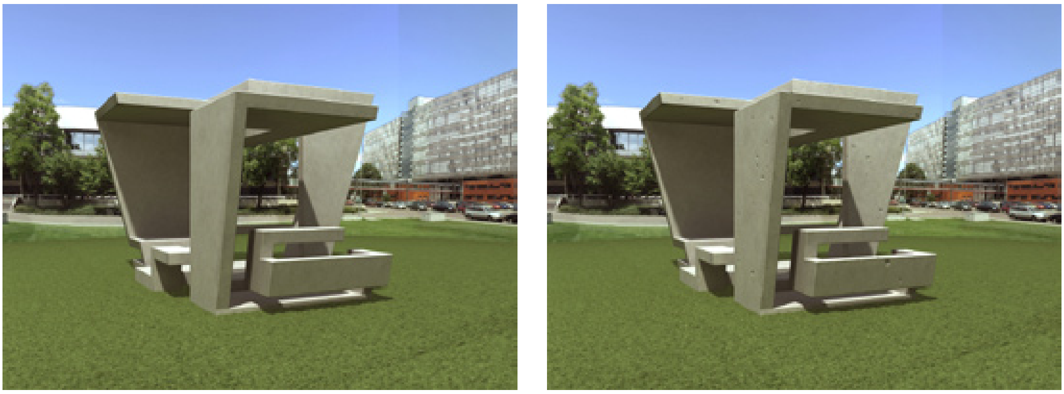
Age 4

Figure 83: using schematic colors we can see clearly the differences between the different material ages

Simulated results

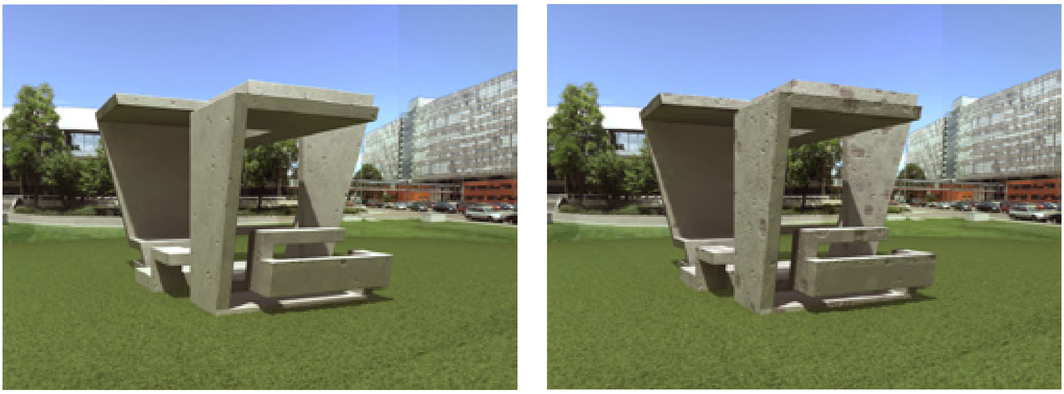
Today's appearance

Simulation at Age 0



Simulation at Age 1

Simulation at Age 2



Simulation at Age 3

Simulation at Age 4

Figure 84, 85 and 86: Weathering sequences of the sculpture from our simulation (examples in higher resolution are available on the cd)


Today's appearance


Simulation at Age 0


Simulation at Age 1


Simulation at Age 2


Simulation at Age 3

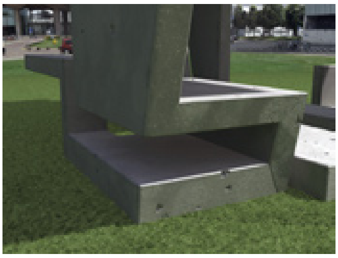

Simulation at Age 4


Today's appearance


Simulation at Age 0


Simulation at Age 1


Simulation at Age 2


Simulation at Age 3


Simulation at Age 4

CONCLUSION AND FUTURE WORKS

Quality level of the results

In this work we have presented two possibilities to generate a weathering simulation of materials which can provide a wide variety of weathering effects: the quicker one uses different textures of material ages and goes from one to another depending on the time. The second one requires a previous simulation to localize weathered surfaces, which operates in the placing method of the different aging materials. By using the second method and weathering maps, we bring a higher level of accuracy in the results: exposed areas are weathering while unexposed do not. But this accuracy has a cost, the simulation is longer and more complex.

These two simulations use a common aging material that we created according to some real examples and some traditional weathering effects. It was created to give accurate results from both close and far point of view. This aging material can be saved in a library, and shared for a future utilization. Appending this library will allow simulations with different materials and expend the possibilities of it.

It is important in our simulation to use a precise 3D model containing all the details since our simulation is geometry-dependent. By using weathering maps, surface details are explicitly defined in three-dimension and may change the object geometry, they are not simply rendered using texture mapping.

Finally, though the preparation of the modell and the weathering maps can take time, the simulation will provide any view to be rendered offering realistic details.

Problems encountered and limits of the simulation

Using different materials and weathering maps in a simulation makes it more complex and demands high computer expenses. While preparing all the parameters manually there is a high probability of entering wrong settings and missing parts of the simulation, involving wrong simulation and little possibility to notice a mistake. Moreover, the difference between the material ages is sometimes really subtle, and can be seen only in the details. Using this methodology to have a global view of a weathered object will consume too long time for few changes.

On this simulation we selected weathering factors from a long existing list of traditional weathering effects. According to articles a theory of weathering materials does not exist, and each case is a unique; so accurate results are still really difficult to predict, a possibility to get closer to them can be made by implementing more weathering factors in the simulation.

Hypothesis on improving the simulation

In a close range goal, we can localize the position of the scratches, cracks and spallings in the simulation. In this work these effects are applied by texture mapping and integrated into the material. To get better results we can imagine another map representing some impacts points. On these impact points, theses effects will be rendered, and they will affect the object geometry directly. We can remark E. Paquette and P. Poulin's work [11] on simulating scratches and aging by impacts.

Furthermore, we could localize the sunlight effect on surfaces producing discoloration (e.g. on wood sun can change strongly the apprearance of the surface material and its color). In this simulation, all surfaces were under light effect, but surfaces exposed to south will change quicker than surfaces exposed to east or west, and north surfaces will get almost any change. To do so, we can imagine that we will use lighting parameters and a heliodon, and render the different shadows in a day. Then we can collapse the different maps to a unique one, showing gradient shadows from full exposed surfaces to no exposed surfaces. To improve the quality of this map, we can also render the shadows from the different seasons, and resume them in an average.

Improving the rainfall rate must be a hypothesis to get more accurate results: here we defined it when the exposed surfaces are mostly covered by particles, so we did not make any use of the rain fall rate from the meteoroligical station. To find the right rate, we might compare results on the same object in different locations, and also compare these results to real examples (in this location this exposed surface has this appearance after ten years, and this appearance after twenty years, and so on...)

The particle system may also be improved in the simulation. Since particles are stopping when they hit a surface, they might have other options: flow onto the surface, bounce and loose speed, or reflect. X. Tong [05] has made a recent work on particle emission to simulate weathering: each particle has a speed parameter when it is thrown in the scene, and gets speed when it is falling down. When it hits an object, the speed parameter will define which kind of action happens to the particle : stop, flow, bounce or reflect. An action will modify the speed parameter of the particle (in the cases of flowing, bouncing and reflecting). Probably that can be defined in the description of the particle emitter, and may require specific programming.

Finally, we can imagine a handy interface to enter the weathering parameters in the simulation. First it will group all these parameters in a unique place, and second any comparison between these factors will be easier. This window should apper at the beginning of the simulation to enter location parameters, but should be also accessible at any time in the simulation. Furthermore, this simulation might be more automatic on the recurring operations, leaving computational results run on their own for the simulation instead being of always required by the user. The interface and automatic settings will not improve the simulation quality but rather give a support to the user.

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