WORKING PAPER

APPROACHES IN MODELING THE IMPACT OF AIR POLLUTION-INDUCED MATERIAL DEGRADATION

Harald Boden

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IIASA
International Institute
for Applied Systems Analysis

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PREFACE

Damage to materials from air pollution is considered to be an important economic factor in society. For this reason, it was decided as part of the 1988 Young Scientist's Summer Program at IIASA to explore the possibility of including a submodel for materials damage in IIASA's Regional Acidification INformation and Simulation (RAINS) model. This Working Paper is the result of this investigation. Although the conclusion of the author is that it is at the present time premature to include materials damage in RAINS, due to a lack of input data, this report contains a wealth of information on existing background data (such as damage functions) and possible analytic approaches once the input data are available. As such, therefore, this paper represents a very important first step in a possible future inclusion of materials damage in a model of transboundary air pollution.

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TABLE OF CONTENTS

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Harald Boden

1. INTRODUCTION

Within the last 20 years people have detected increased damages to materials exposed to the natural environment. These damages are believed to exceed by far those detected in previous centuries. Scientific research reveals that these additional damages have been caused by a change in the chemical composition of the air due to increased industrial activity.

One can conclude from the literature that material degradation plays an economically important role in society. This paper has to be seen in the light of the Transboundary Air Pollution Project at IIASA. Since 1984 this Project has been developing the Regional Acidification INformation and Simulation (RAINS) model to formulate and assess European strategies for reducing the transboundary flow of SO_2 and NO_x, and the resulting ecological damage. Until now the Project has not considered material degradation from air pollution; an important aspect of the economic impact of air pollution may therefore have been neglected. The author's task as participant of IIASA's Young Scientists Summer Program (June to August 1988) was to carry out a literature search on known relationships between air concentrations and depositions on the one side, and building material damage on the other side. If possible these relationships should be quantified and a recommendation would be made as to whether or not it is possible or advisable to include these relationships in the RAINS model.

The literature search revealed a huge number of books and articles that deal with the theme of atmospheric corrosion and material degradation by air pollution, but the author found only three reports that deal directly with the economic assessment on a highly aggregated level of material damage from air pollution (Stankunas *et al.*, 1983; McCarthy *et al.*, 1984; Horst *et al.*, 1986). These authors developed several approaches for the economic assessment of material damage that can be used in a simulation model on a computer. These approaches are described in Section 3.2.

This paper can be considered to be a methodological study and review. In the three months available for the work it was not possible to spend much time on collecting data and building a database for later computational purposes. In fact, many of the data which would be necessary for building a computer model on material degradation by air pollution are not easily available and it will take a large amount of time to acquire them.

Chapter 2 below describes the principal interactions between air pollutants and materials exposed to them. Chapter 3 explains how these material damages can be measured and economically rated. In the next chapter the reader will find a description of how a formal model describing air pollution-induced material degradation can be developed. Chapter 5 points out the restrictions in building such models. Lastly, Chapter 6 contains a proposal for how air pollution-induced material degradation could be included into the RAINS model.

2. TYPES OF MATERIAL DAMAGE AND DAMAGE MECHANISMS

2.1. Damage Types and Principal Damage Mechanisms

The literature lists the following damages which are at least partially caused by air pollutants:

- Corrosion and tarnishing of metals and electrical components.
- Soiling and eroding of building surfaces.
- Surface erosion, discoloration and soiling of paints and organic coatings.
- Fading, soiling and reduced tensile strength of dyed materials.
- Cracking of rubber.
- Cracking and weakening of plastics.
- Spalling of bricks.
- Deterioration of roofing materials.

These damages are caused by interactions between materials and natural or anthropogenic air components. On the following pages, the principal mechanisms that lead to material damage will be explained. Afterwards, each material will be covered separately.

Atmospheric deterioration is influenced by the following natural factors:

- moisture;
- temperature (mean value and variations);
- sunlight;
- air movement (wind speed and direction);
- other factors (sea salt, fog).

It should be noted that *moisture* is an important determinant of atmospheric corrosion. Without moisture in the atmosphere, there would be little atmospheric corrosion, even in severely polluted environments. It has been proven that wetting of metal's surface produces a sharp increase in the corrosion rate. Yocum and Upham (1977) collected the information which is shown in *Table 2.1.*

Table 2.1. The role of humidity in atmospheric corrosion.

Metal	*Critical humidity at which corrosion increases*	*Authors*
Aluminum	80% in air containing SO_2	Sanyal and Bhadwar (1959)
Mild steel	60% and 75%	Sanyal and Bhadwar (1959)
Nickel	70% in presence of SO_2	Aziz and Godard (1959)
Copper	63% in presence of SO_2	Aziz and Godard (1959)
Zinc	70% in unpolluted air	Aziz and Godard (1959)
Magnesium	90% in unpolluted air	Aziz and Godard (1959)

Other experiments (e.g., Vernon, 1935) indicate that corrosion at relative humidities below 60% is minimal. As the relative humidity increases from 60% to 80% or even greater, the protective oxidized layer on the metal surface breaks down and allows corrosion. Moisture in the form of rain may, however, reduce atmospheric corrosion by washing away dangerous pollutants.

The *temperature* influences the chemical reaction rate causing deterioration. If changes in temperature cause the material's surface temperature to fall below the dew point, then the surface becomes moist and, as a consequence, chemical reactions may take place. Most chemical reactions that result in corrosion are diffusion-controlled, so that temperature below the freezing point will lead to a sharp decrease in the corrosion rate. Nevertheless, freezing-thawing cycles can lead to deterioration through stress caused by expansion and contraction of water in the pores of the material.

Air movement, especially wind speed, are significant in determining deposition rates, and whether or not solid and liquid agents impact on vertical surfaces settle on horizontal surfaces, or lead to abrasion.

Sunlight promotes the drying of material surfaces, but on the other hand, ultraviolet radiation deteriorates some organic building materials.

Among the other factors, sea salt plays an important role as a precursor of corrosion and deterioration.

The following damage mechanisms can be distinguished:

- abrasion;
- direct chemical attack;
- dissolving attack;
- driving attack;
- indirect chemical attack;
- electrochemical corrosion.

Material deterioration by *abrasion* is caused by solid particles of sufficient size, traveling at high velocities and striking the material.

Direct chemical attack means that air pollutants react irreversibly and directly with material to cause deterioration. One must distinguish between a driving and a dissolving attack. During a *dissolving attack* the air pollutant reacts with the material to form a water soluble salt. This salt may be transported away or may be washed away from the surface. *Driving attack* follows a dissolving attack, if the originally dissolved substances crystallize. The uptake of water into the crystalline structure leads to a substantial volume increase which may lead to splitting of the material.

Indirect chemical attack takes place if the absorbed pollutants undergo chemical reactions, with the reaction products attacking the material under consideration.

Electrochemical corrosion is an important mechanism that leads to the damage of ferrous metals: Small electrochemical cells result from physical differences on the metal surface. When water is present, currents flow due to differences in potential between anodes and cathodes. Ionic air pollutants increase the conductivity of the surface water and will increase the rate of corrosion.

2.2. Damage Mechanisms Classified by Material

Materials are usually classified as:

- Metals
  - Ferrous metals
    - iron
    - steel
  - Non-ferrous metals
    - aluminum
    - zinc
    - copper
- Inorganic building materials
  - Natural rocks
    - sandstone
    - limestone
    - marble
    - basalt
  - Cementitious materials
    - concrete
    - reinforced concrete
    - mortar
    - plaster
    - brick
- Organic materials
  - Wood
  - Plastics
  - Paints
  - Leather
  - Textiles made of natural fibers

The following substances in the atmosphere are usually responsible for material deterioration:

- Sulfur dioxide
- Carbon dioxide
- Hydrogen sulfide
- Nitrogen oxides
- Ammonia
- Chlorine
- Hydrochloric acid
- Chlorides

- Organic acids

In the following sections, the damage mechanisms for the three material groups: metals, inorganic building materials and organic materials, will be explained. *Table 2.2* offers an oversight on building materials, associated damages and potential damage precursors.

Table 2.2. Air pollution damage to materials. (Source: Yocum and Baer, 1983).

Material	*Type of impact*	*Principal air pollutants*	*Other environmental factors*
Metals	Corrosion, tarnishing	Sulfur oxides and other acid gases	Moisture, air, salt, particulate matter
Building stone	Surface erosion, soiling, black crust formation	Sulfur oxides and other acid gases	Mechanical erosion, particulate matter, moisture, temperature fluctuations, salt, vibration, CO_2, microorganisms
Ceramics and Glass	Surface erosion, surface crust formation	Acid gases, especially containing fluoride	Moisture
Paints and Organic Coatings	Surface erosion, discoloration, soiling	Sulfur oxides, hydrogen sulfide	Moisture, sunlight ozone, particulate matter, mechanical erosion, microorganisms
Paper	Embrittlement, discoloration	Sulfur oxides	Moisture, physical wear, acidic materials introduced in manufacture
Photographic Materials	Microblemishes	Sulfur oxides	Particulate matter, moisture
Textiles	Reduced tensile strength, soiling	Sulfur and nitrogen oxides	Particulate matter, moisture, light, physical wear, washing
Textile Dyes	Fading, color change	Nitrogen oxides	Ozone, light, temperature
Leather	Weakening, powdered surface	Sulfur oxides	Physical wear, residual acids introduced in manufacture
Rubber	Cracking		Ozone, sunlight, physical wear

Metals

The most important substance involved in the atmospheric deterioration of metals is sulfur dioxide. Near the sea, chlorides also have a great importance.

The corrosion rate of *ferrous metals* is determined by two factors, namely the time of wetness and the rate of sulfur deposition. The corrosion itself is an electrochemical process (see electrochemical corrosion, Section 2.1) that operates in the presence of water. Any dissolved air pollutant ions that may be present increase the conductivity and, therefore, the rate of corrosion.

Aluminum and *copper* are relatively resistant to the effects of air pollution because these metals develop a protective coating on their surface. Nevertheless, these coatings can be attacked by acids such as sulfuric acid, so that the corrosion rates in urban industrial areas are higher than those in rural atmospheres.

In outdoor environments, *zinc* is used very often to protect ferrous metals from corrosion. Air pollution is the most important determinant of zinc corrosion because it destroys the protective coating that forms under natural conditions.

Inorganic Building Materials

Research into the deterioration of inorganic building materials has concentrated for a long time on sulfur compounds because only minor traces of nitrates have been found on the surfaces of building materials. However, this may be a misinterpretation of measurements, since calcium nitrate is a highly soluble salt.

The uptake of air pollutants by *natural rocks* takes place by dry or wet deposition. SO_2 and its reaction products are considered to be the most important substances influencing the deterioration of stone. The dry deposited SO_2 and sulfur particles are not harmful unless they become wet.

In considering the damage to natural rocks, we must distinguish between the direct acid reaction with the stone surface, and reactions taking place inside the stone. On the rock surface, sulfur compounds react with the carbonates in natural rocks (e.g., $CaCO_3$ in limestone, marble and calcareous sandstone) to form easily soluble salts such as gypsum (calcium sulphate, $CaSO_4$) and ettringite (calcium suphoaluminate hydrate). As a result of this chemical reaction the zones on marble, limestone and calcareous sandstone monuments that experience run-off become thinner.

On stone areas where no run-off takes place, but which become wet from time to time, deposited sulfur products and chemical reaction products form black crusts. In times of wetness these black crusts become dissolved and the resulting acid solution is very harmful to the stone below.

Transport of air pollutants inside the stone takes place by diffusion processes, e.g., SO_2 from the environment is able to react with humidity inside the stone to form sulfurous acid. However, capillary transport of surface sulfurous acid into stone pores is a more important process.

The sulfur acid inside the stone reacts with the building material to form gypsum and ettringite, which then become dissolved. The gypsum and ettringite in solution may be transported to the stone surface where it may be washed away easily.

Drying causes the gypsum and ettringite to crystallize. Binding crystal water causes a two-fold volume increase and, if it takes place inside the stone, the resulting tension may cause splitting in the stone and accelerate stone decay.

In considering the damage to *cement concrete* and *reinforced concrete*, we must distinguish between the damage caused by carbon dioxide and the damage caused by sulfur products.

Carbon dioxide itself is not harmful to concrete unless it reacts to form carbonic acid and becomes transported into concrete pores, leading to a process called carbonation. In the carbonation process, which starts at the outside and proceeds to the inside of a component, calcium hydroxide [$Ca(OH)_2$] and carbonic acid react to form calcium carbonate ($CaCO_3$). At the same time, the pH of the alkaline pore water decreases. This process is very important for reinforced concrete, because the carbonation front reaching the steel reinforcement causes the loss of the steel's protective alkaline layers; as a consequence the steel starts rusting. Rust causes a volume increase, so that resulting tension inside the cement paste may lead to cracking, blistering and spalling of the surface.

Carbonic acid may also react with various calcium compounds present in cement paste to form soluble salts. If dissolved, these salts may be transported to the surface and washed away. Crystallization processes inside the cement paste may increase stone breakup. Damaging mechanisms of sulfur compounds to concrete are similar to those described for limestone, marble and calcareous sandstone. Most important is the transformation of calcium carbonate to calcium sulfate.

Soluble salt crystallization is regarded as the main mechanism in the deterioration of *brick* and *mortar*. The mechanisms that lead to the salt formation are similar to those described for limestone, mortar and calcareous sandstone: the uptake of sulfur compounds and the following chemical reactions that result into the formation of gypsum and ettringite. The degradation of brick and mortar is another form of masonry degradation. Both materials can be deteriorated by air pollutants and the interaction between these two materials decides which one will be deteriorated more. Actually, where the evaporation of the salt-containing solution occurs is important, because the salt will concentrate there and during a dry period crystallization may lead to the destruction of either brick or mortar. Usually the evaporation will be higher in a more porous material, so that the question which of the materials will be destroyed can only be answered in the context of pairs of bricks and mortars on the one hand and the humidity acting on the brick masonry on the other hand.

Organic Materials

Atmospheric pollutants play no important role in the atmospheric deterioration of *wood*.

Air pollution in form of NO_x accelerates the aging of *plastics* but no material could be found that described this mechanism quantitatively.

Cracking, peeling, erosion and discoloration are the main damage types for *paint*. Surface erosion can be partially ascribed to SO_2, whereas peeling and cracking are caused by moisture from inside the building. The rate of surface erosion is measured by the loss of thickness of the paint layer resulting from the chemical action of sulfur oxides, hydrogen sulfide, ozone, moisture and sunlight. It is not possible to give general statements on the importance of sulfur oxides for paint damage because of the great number of different paints in use and the fact that other environmental factors cause the same type of damage. For buildings, soiling from air pollution plays an important role in that more frequent repainting is required as a result.

3. THE MEASUREMENT AND ECONOMIC ASSESSMENT OF MATERIAL DAMAGE

3.1. Damage Functions

The term "damage function" here denotes a mathematical dose-response function connecting material damage to the factors involved in the damaging process, e.g.:

$$y = f(x_1, x_2, \ldots, x_n)$$

where y = damage (weight loss, loss in thickness, etc.), x_i = concentration of harmful substances or time of wetness, temperature, etc. These damage functions are widely used to describe atmospheric corrosion and atmospheric deterioration. In contrast to the physical damage function described above, an economic damage function converts the physical damage into economic terms.

Damage functions from different sources are listed below for various materials:

Metals:

Steel:

(S.1) *Carbon steel* [1][1]: $R^2 = 0.91$

$$Y = 9.013 * e^{0.00161 * SO_2} * (4.768 * t)^{(0.7512 - 0.00582 * OX)}$$

where:

Y = depth of corrosion (μm)

SO_2 = average concentration ($\mu g/m^3$)

OX = average concentration of oxidants ($\mu g/m^3$)

t = time of exposure (years)

(S.2) *Copper-bearing steel* [1]: $R^2 = 0.91$

$$Y = 8.341 * e^{(0.00171 * SO_2)} * (4.351 * t)^{(0.8151 - 0.00642 * OX)}$$

where:

Y = depth of corrosion (μm)

SO_2 = $\mu g/m^3$

OX = $\mu g/m^3$

t = time (years)

1

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[1]Sources:

[1] Gillette and Upham (1973) and Park (1974), from Liu and Yu (1978).

[2] Gillette (1975), from Stankunas *et al.* (1983).

[3] Guttman and Sereda (1968), from McCarthy *et al.* (1984).

[4] Haynie *et al.* (1976), from McCarthy *et al.* (1984).

[5] Haynie *et al.* (1976), from McCarthy *et al.* (1984).

(S.3) *Weathering steel* A[2] [1]: $R^2 = 0.91$

$$Y = 8.876 * e^{(0.0045 * SO_2)} * (3.389 * t)^{(0.6695 - 0.00544 * OX)}$$

where:

Y	= depth of corrosion (μm)
SO_2	= $\mu g/m^3$
OX	= $\mu g/m^3$
t	= time (years)

(S.4) *Weathering steel* B [1]: $R^2 = 0.91$

$$corr = [5.64 * \sqrt{SO_2} + e^{(55.44 - 31,150 / R*T)}] * \sqrt{t_w}$$

where:

corr	= depth of corrosion (μm)
SO_2	= ($\mu g/m^3$)
R	= 1.9872 cal/g - mole °K
T	= geometric mean temperature of the specimen when wet in °K
t_w	= time of wetness (years)

(S.5) *Enameling steel* A [1]:

$$corr = 183.5 * \sqrt{t} * e^{(0.06421 * Sul - 163.21/RH)}$$

where:

corr	= depth of corrosion (μm)
SO_2	= $\mu g/m^3$
t	= time (years)
Sul	= average level of sulfate in suspended particulate ($\mu g/m^3$)
RH	= average relative humidity (%)

(S.6) *Enameling steel* B [1]:

$$corr = 325.0 * \sqrt{t} * e^{(0.00275 * SO_2 - 163.2/RH)}$$

where:

corr	= depth of corrosion (μm)
SO_2	= $\mu g/m^3$
t	= time (years)

[2] A,B denote different damage functions for the same material.

RH = average relative humidity (%)

(S.7) *Galvanized steel* [1]: $R^2 = 0.91$

$$corr = [0.0187 * SO_2 + e^{(41.85 - 23{,}240/RT)}] * \sqrt{t_w}$$

where:

corr = depth of corrosion (μm)
SO_2 = $\mu g/m^3$
t_w = time of wetness (years)

Zinc:

from [1] $R^2 = 0.92$

$$Y^* = 0.001028 * (RH - 48.8) * SO_2$$

where:

Y^* = zinc corrosion rate (μm/year)
SO_2 = $\mu g/m^3$
RH = average relative humidity (%)

from [2]

$$CR = 0.00103 * (RH-49) * (SO_2)$$

where:

CR = corrosion rate of zinc in microns per year
RH = relative humidity (%)
SO_2 = concentration of SO_2 ($\mu g/m^3$)

from [3]

$$Y = 0.00546 * A^{0.8152} * (B + 0.02889)$$

where:

Y = weight loss due to corrosion in g/3 in. × 5 in. panel
A = time of wetness (hours)
B = concentration of SO_2 (ppm)

from [4]

$$corr = [0.0187 * SO_2 + e^{41.85 - 23{,}240/(R^*T)}] * t_w$$

where:

corr = thickness loss (μm)
SO_2 = SO_2 concentration ($\mu g/m^3$)
T = temperature (°K)

R = gas constant (1.9872 cal/g-mole)
t_w = time of wetness (years)

For a comparison of zinc damage functions see also McCarthy *et al.* (1984). It turns out that the damage function depends strongly on the type of structure under consideration. Therefore, McCarthy *et al.* (1984) used the following damage function:

$$C = (A + B * SO_2) * t_w$$

where:

C = zinc corrosion rate (μm/year)
A = corrosion rate when wet in a clean environment (2.4 μm/year)
B = 0.0225 for roofing and siding and 0.0450 for fencing.
t_w = time of wetness (years)

Paints:

Oil base house paint [1]: $R^2 = 0.61$

$$\text{Erosion rate} = 14.323 + 0.01506 * SO_2 + 0.3884 * RH$$

where:

SO_2 = $\mu g/m^3$
RH = average relative humidity (%)

Acrylic coil coating [1]:

$$\text{erosion rate} = 0.159 + 0.000174 * O_3$$

where:

O_3 = ozone ($\mu g/m^3$)

Paint [5]

$$E = (10 + 0.03 * SO_2) * t_w$$

where:

E = erosion (μm/year)
SO_2 = annual average SO_2 ($\mu g/m^3$)
t_w = time of wetness (years)

Fabrics:

Plain fabric [1]: $R^2 = 0.70$

$$\text{Erosion rate} = dE = 30 * \left[1 - e^{-(2.57 + 3.38 * 10^{-5} * M * NO_2) * t}\right]$$

where:

dE	= amount of fading, in fading units
NO_2	= $\mu g/m^3$
M	= amount of moisture ($\mu g/m^3$) at 25°C and one atmosphere
t	= time (years)

Soiling of building materials:

Oil base paint [1]: $R^2 = 0.74$

$$\text{Reflectance} = 89.43 - 0.2768 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Tinted base paint [1]: $R^2 = 0.738$

$$\text{Reflectance} = 86.13 - 0.2618 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Sheltered acrylic emulsion paint [1]: $R^2 = 0.88$

$$\text{Reflectance} = 91.54 - 0.593 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Acrylic emulsion paint [1]: $R^2 = 0.902$

$$\text{Reflectance} = 90.79 - 0.4131 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Shingles [1]: $R^2 = 0.769$

$$\text{Reflectance} = 43.50 - 0.199 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Coated yellow brick [1]: $R^2 = 0.503$

$$\text{Reflectance} = 43.21 - 0.1133 * \sqrt{SP * t}$$

where:

Reflectance	= a measure of soiling (%)
SP	= suspended particulate ($\mu g/m^3$)
t	= time (months)

Sources:

[1] Gillette and Upham (1973) and Park (1974), from Liu and Yu (1978).
[2] Gillette (1975), from Stankunas *et al.* (1983).
[3] Guttman and Sereda (1968), from McCarthy *et al.* (1984).
[4] Haynie *et al.* (1976), from McCarthy *et al.* (1984).
[5] Haynie *et al.* (1976), from McCarthy *et al.* (1984).

For further damage functions see *Table 3.1.*

Some of the above equations contain a term called time-of-wetness. This is a measure of the presence of moisture on a metal's surface. Haynie (1986) defines it as follows: "Time-of-wetness is the time a critical relative humidity is exceeded and the dew point is greater than 0°C, plus any time the critical humidity is not exceeded and it is raining". He used regression analysis to calculate relative humidity (on an hourly basis) as a function of dew points above 0°C and temperature, resulting in the equation:

$$RH = 100 * e^{[(-0.0722 + 0.00025)(T + DP)(T - DP)]}$$

where:

RH	= relative humidity
T	= temperature
DP	= dew point

In two earlier studies, Haynie (1986) derived empirical relationships between relative humidity and time-of-surface-wetness:

(a) from Haynie *et al.* (1976):

$$f_w = e^{(4.04 - 4.04/RH_w)}$$

Table 3.1. Damage functions for steel, zinc and galvanized steel (after United Nations Economic Commission for Europe, 1984; Table 11 from Harter, 1986).

Equations	*Significant parameters*
Steel	
$z = 0.16tw^{0.7}(SO_2 + 1.78)$	tw SO_2
$y = 9.013(e^{0.0016SO_2})(4.768t)^{0.7012} - 0.00582\ ox)$	SO_2 t Oxidant
$y = a_0\ t[e^{(a_1x - a_2/RH)}]$	Enameling steel t $x = SO_4$ or SO_2 RH
$y = \left[5.64/SO_2 + e\left[55.44 - \frac{31.150}{RT}\right]\right] tw$	Weathering steel SO_2
$\log rate = 0.702 - 0.588 \log t - 0.004\ TS$ $+ 0.006\ SO_2 + 0.011\ H_2S - 0.010\ NO_x$ $+ 0.006\ TSP - 0.005\ SO_4 - 0.001\ NO_3$	Weathering steel time Total Sulfur (TS) SO_4^{2-} Total Suspended Particulates (TSP)
Monthly rate $y = 1.54\ SO_2 + 2.34\ NPREC$ $+ 0.05\ H^+ - 15.2$ y = monthly corrosion rate of steel	$SO_2\ \mu g/m^3$ No. of days with precipitation H^+
$y = 0.0106\ SO_2 + 2.0$	Carbon steel, SO_2
$y = 5.28\ SO_2 + 176.6$	SO_2 in g/m^3 Annual rates
$y = 1.17\ tw^{0.66}(SO_2 + 0.048)$	tw SO_2
$y = [(2.0 \times 10^{-3} + 7.3 \times 10^{-3}\ T)\ tw$ $+ (1.43 + 6.0 \times 10^{-2}\ T)(SO_2)]$	Temperature (T) SO_2, t_w y in $g/m^2/y$
$y = 71.99\ tw^{0.386}\ SO_2^{0.556}$ Corrosion loss over 3,650 days $y = 0.0152\ t_w\ 0.428\ SO_2\ 0.570$ Steady corrosion rate	SO_2 in $mg/m^2/d$ tw = hrs RH>80% and $t > 0°C$
$y = 1.445 \times 10^{-2}(H_2O)^{0.824}\ SO_2^{0.458}$	H_2O = no. hrs with $RH > 80\% = t_w$ SO_2 in $mg/m^2/d$

y = corrosion depth (μm)
SO_2 in $\mu g/m^3$
tw = time of wetness (y)
T = mean panel temperature when wet (K)
R = 1.9872 cal/g mol
t = exposure time
z = corrosion loss (mg/area)
ox = oxidant (mg/m^3)
RH = average relative humidity (%)

Table 3.1 (continued). Damage functions for steel, zinc and galvanized steel [after United Nations Economic Commission for Europe (1984); Table 11 from Harter (1986)].

Equations	*Significant parameters*	*Reference*
Zinc		
$K = 0.00076\ tw^{0.50}\ SO_2^{0.718}$	tw = total time RH > 80% t > 0°C in terms of hrs/day calc. from linear reg. averages.	10-year extrapolation
$K^1 = 1.4 tw^{0.51} SO_2^{0.72}$	SO_2 daily averages K = corrosion loss or rate in $g/m^2/day$	
$K = 0.001028\ (RH\text{-}48.8)SO_2$	K = corrosion rate = μm/exposure time. Av. SO_2	Haynie and Upham, 1976
$K = 0.22SO_2 + 6.0$ $K = 0.27Cl + 0.22SO_2 + 4.5$	Corrosion rate $g/m^2/y$ $SO_2\ \mu g/m^3$, $Cl^-\ g/m^2/y$	
$K = 0.03SO_2 + 0.01RH > 90\% + 1.6$ (rural, urban, industrial sites) Correlation coefficient R = 0.54 $K^1 = 0.06SO_2 - 0.14T + 2.3$ (urban, industrial) Correlation coefficient R = 0.78	K = Monthly corrosion rate g/m^2, $SO_2\ \mu g/m^3$ RH > 90 time in hrs. when RH > 90% K^1 = monthly corr. rate g/m^2 T = monthly mean temperature	Haagenrud *et al.*, 1982
$Y = 0.204\ (SO_2) + 2.46$	$SO_2\ \mu g/m^3$, $y = g/m^2/y$	
$K = 0.0049 tw^{0.91}\ (SO_2 + 0.05)$	tw = time RH > 85%, $SO_2\ \mu g/m^3$ K = corrosion rate $\mu m/y$	
$K = [2 \times 10^{-4} + 2.0 \times 10^{-4}T) + (5.5 \times 10^{-2})\ (SO_2)]\ tw$	K = total corr. rate $g/m^2/y$, T = temperature, $SO_2\ \mu g/m^3$ tw = time of wetness hrs/y = $\frac{tRH80\%}{2}$	
Galvanized steel		
$K = (0.0187SO_2)+(e^{41.85-23.24/RT})tw$	K = corrosion loss tw = wetness time, $SO_2\ \mu g/m^3$ T = temp., R = gas constant	Haynie *et al.*, 1976
$y = 0.45SO_2 + 0.7$	SO $\mu g/m^3$ $y = g/m^2/y$	Norwegian Function for Economic Assessment
$\log V(t)=1.977-0.144 \log t$ $\log V(t)=1.863-0.102 \log t+0.004TS$ $-0.005\ SO_2 + 0.0054\ H_2S - 0.065\ O_3$ $-0.002\ NO_x + 0.003\ TSP - 0.008\ SO_4$ $+0.018\ NO_3$	Vt = corrosion rate t = exposure time TSP = total suspended particulate TS = total sulfur	Mansfield, 1980
rate $(g/m_2/yr) = 13.8 - 85.39.I^2$ $+0.022SO_2.I + 1.27I.SO_2$	I = intensity of rainfall $I.SO_2$ = intensity × SO_2 $SO_2.I$ = initial weighted average for first six months of exposure ($\mu g/m^3$)	Saunders, 1982 Simplified equation for cost benefit analysis

y = corrosion depth (μm)
SO_2 in $\mu g/m^3$
tw = time of wetness (y)
T = mean panel temperature when wet (K)
R = 1.9872 cal/g mol

t = exposure time
s = corrosion loss (mg/area)
ox = oxidant (mg/m^3)
RH = average relative humidity (%)

where:

RH_w = annual average relative humidity

f_w = fraction of time that the surface is wet

(b) from Haynie (1980):

$$f = [(1 - k) * RH] / (100 - k * RH)$$

where

f = fraction of time the relative humidity exceeds the critical value

RH = average relative humidity

k = empirical constant (<1.0)

Stankunas *et al.* (1983) used another function, also derived by Haynie (1980b), to estimate the time of surface wetness:

$$f_w = e^{[-3.35 * (100-RH)/RH]}$$

where

f_w = fraction of time that the surface is wet.

RH = average relative humidity.

3.2. Calculating the Economic impact

(a) General Considerations

The economic importance of material degradation caused by air pollutants has to be seen in the light of the expected service life of the material. In the author's opinion, an economic damage takes place if the service life is shortened, if additional maintenance measures are necessary to ensure full usefulness during the service life or, if more resistant and more expensive materials have to be used. These economic dis-benefits of air pollution are usually classified as follows:

(i) *Direct damage costs*

Under direct damage costs, all costs for the repair and replacement of materials damaged by air pollutants are summed.

(ii) *Avoidance costs*

Avoidance costs are the sum of all costs spent for additional maintenance measures and for using resistant but more expensive materials.

(iii) *Aesthetic or physiological costs*

In this category we summarize all costs that are not primarily connected with the material's performance, such as additional window cleaning in more polluted areas. This cost category is determined by personal opinions on how a building or building component should look. The importance of this cost category in economic terms is difficult to estimate because there are few data available that relate people's opinion on the outer appearance of their housing to additional expenditures for cleaning, repainting or other maintenance measures. Where data are available, it is difficult to tell if the additional costs fall into the category of direct damage costs due to paint blistering and peeling off, or into the category of aesthetic costs due to an untidy appearance.

In calculating the economic impact of air pollutants, one has to pay attention to the possibility that other environmental factors, e.g., salt in maritime environments, may cause much greater damage to materials than air pollutants. In those cases, additional maintenance measures or replacement actions are primarily induced by non-anthropogenic factors. Their costs, therefore, cannot be included in the sum of air pollution-induced damages, although minor damages caused by air pollutants may be repaired at the same time.

Some estimates of the amount of economic damage caused by air pollution are as follows:

The corrosion study NBS-BCL (Anon, 1978) points out that, for the United States in 1975, the value of corrosion damage reached about 4% of the GNP. Because air pollution contributes only a small part of this corrosion damage, the actual value of air pollution-induced corrosion damage must be much lower than 4% of the GNP. Passaglia (1986) cites different estimates and concludes that, for the United States, about 4% of the corrosion damage to metals is caused by air pollutants, so that the air pollution-induced corrosion damage summarizes to about 0.15% of GNP.

Freeman (1979), Waddel (1971) and Yocum and Grappone (1977) estimated the values summed in *Table 3.2.*

For the Federal Republic of Germany, Heinz (1986) describes economic losses caused by air pollution, as listed in *Table 3.3.*

For estimating the economic impact of material degradation by air pollution, Stankunas *et al.* (1983) and McCarthy *et al.* (1984) propose two different approaches, namely, the comparative approach and the analytical approach.

(b) The Comparative Approach

The comparative approach compares the lifetime or maintenance costs in two environments experiencing different degrees of air pollution. By comparing lifetimes or maintenance costs, one gains quantitative relationships between air pollution and economic damage.

Table 3.2. Estimates of materials damage attributed to SO_2 and PM in 1970 (in Million of 1970 Dollars), from U.S. Environmental Protection Agency (1981).

	ESTIMATES						
	Waddell (1971)			*Yocom and Grappone (1977)*			*Freeman (1979)*
Material Category	SO_x	*PM*	*Total*	SO_x	*PM*	SO_x/*PM Total*	SO_x/PM[a]
Paints	100	100	200	200	500	700	704
Textiles and Dyes	--	--	--	--	--	636	Salvin, 1970
Metal Corrosion[b]	400	--	400	400	--	400	400
Electrical Switches and Components	included in metal corrosion			included in metal corrosion			80
Other[c]	100	200	300	300	100	400	400
Total	600	300	900	900	600	1,500	2,200

[a]No allocation of cost to PM or SO_x specifically.
[b]Nickel, tin, brass, bronze, magnesium, gray iron, malleable iron, chromium, molybdenum, silver, gold, clay pipe, glass, refractory ceramics, carbon, and graphite.
[c]Waddell (1971) used earlier version of Gillette's (1975) report.

Table 3.3. Economic losses caused by air pollution (Umweltbundesamt, 1986).

Category	*Losses, Mill. DM (1983)/a*
Damage to buildings:	
Painting of windows, house doors, metal railings, other maintenance measures	699
Facade painting	1014
Renewal of eaves	409
Damage to steel structures:	
Highway bridges, including railings	21
Railway bridges	6
Transmission towers	6
Railway poles including supporting pillars	11
Additional cleaning effort:	
Windows	142

The steps that have to be taken if one wants to calculate the air pollution damage for a specific area are described by Algorithm 1.

Algorithm 1: Calculating the economic damage from air pollution, using the comparative approach.

1. Find/choose areas with similar atmospheric conditions for all factors, except for air pollution.
2. Determine service life and/or maintenance intervals and costs for specified materials.
3. Build empirical relationships for each material, that connect air pollution and economic damage from air pollution.
4. Build a material inventory for the area under consideration. Determine the amount of each material that is exposed to air pollutants.
5. Use air quality information and data gained in (3) and (4) to calculate the economic damage during a given period.

This approach is a very simple one, but nevertheless it is applicable with regard to the present state of knowledge in the field of material degradation by air pollution on a macro level. However, the uncertainty in this approach is not greater than that in other approaches, as we will see later on in this paper.

The uncertainty in the comparative approach results from uncertainties in the material inventories and the choice of comparable areas. In reality, almost no directly comparable environments exist. The comparative approach tries to overcome this flaw by selecting only several basic atmospheric environment classes, e.g.:

(i) Rural atmospheric environment.
(ii) Suburban atmospheric environment.
(iii) Industrial or downtown atmospheric environment.

For each of these classes and for each material under consideration one has to find information on:

- the length of maintenance intervals;
- the costs for each maintenance action per unit of material;
- the expected service life for the materials under consideration, and the economic value per amount of material;

Heinz (1986) describes values for maintenance intervals in *Table 3.4*.

Pihlajavaara (1980) gives a summary of the recommended maintenance intervals of some paintings and coverings, as listed in *Table 3.5*.

Knowing these values and the amount of material under risk for an atmospheric environment class, calculating the economic damage is a question of simple calculation:

Table 3.4. Maintenance intervals in dependence of air quality (Heinz, 1986).

Category	*Maintenance or replacement intervals (years)* Polluted environment	Clean air
Damage to buildings:		
Painting of windows, house doors, metal railings, other maintenance measures	4	7
Facade painting	6	11
Renewal of eaves	10	30
Damage to steel structures:		
Highway bridges, including railings	10	20
Railway bridges	18	18
Transmission towers	8	14
Railway poles including supporting pillars	10	30
Additional cleaning effort:		
Windows	1/6	1/4

Specific maintenance costs (SMC):

$$SMC_i = MCMAAM \ / \ LMI_i \qquad i \in \{1,...,k\} \tag{1}$$

where:

MCMAAM = maintenance costs per maintenance action and per amount or unit of material.

LMI_i = length of maintenance interval.

k = number of atmospheric environment classes.

Air pollution level specific maintenance costs (APLSMC):

$$APLSMC_i = SMC_i - SMCU \qquad i \in \{1,...,k\} \tag{2}$$

where:

SMC_i = specific maintenance costs.

SMCU = specific maintenance cots in an unpolluted area.

Specific reduced service life costs (SRSLC):

$$SRSLC_i = (VPUM/SLU) * (SLU - SL_i) \qquad i \in \{1,...,k\} \tag{3}$$

Table 3.5. A summary of the recommended maintenance intervals of some paintings and coverings, in years (Pihlajavaara, 1980).

	Recommended length of maintenance intervals			
Building components	*Finland*	*Sweden*	*East Germany*	*Average uncertainty of values*
Inside paint of window casing				
Windows on the shady side	12			±2
Windows on the sunny side (and others not mentioned)	10	14	5	
Outside paint of window casing				
Windows on the shady side	8	7	5	±2
Windows on the sunny side	6	7	3	±2
Painting of inner doors	12	14	10	±2
Varnishing of inner doors	10			±2
Painting of sheet-iron roofing				
Industrial atmospheres	8			
Rural atmospheres	10	7	5	±2
Renewal of tiled roofing	over 20			
Painting of plastered partition walls	12	7		±2
Painting of concrete exterior walls	12	20	10	±2
Painting of concrete floors	10			±2
Covering of floors with plastic plates	25	20	25	±5
Covering of floors with linoleum	23	20		±3

where:

VPUM = value per unit of material.
SLU = service life in an unpolluted area.
SL_i = service life in class i.

Economic material damage from air pollution (EMDAP):

$$EMDAP_i = (APLSMC_i + SRSLC_i) * AMEAP_i \quad i \in \{1,...,k\} \tag{4}$$

where:

$SRSLC_i$ = specific reduced service life costs.
$APLSMC_i$ = air pollution level specific maintenance costs.
$AMEAP_i$ = amount of material exposed to air pollution.

The comparative approach does not account for the possibility that a more expensive but more resistant material may be used because of air pollution.

(c) The Analytic Approach

The analytic approach expresses the interactions between specific air pollutants and the materials under consideration. For each combination of air pollutant and material, this analysis results in a specific physical damage function (see Section 3.1). In the analytic approach, a critical damage level determines at which point maintenance measures are taken or replacement is necessary. From the knowledge of a specific physical damage function, air quality information and the critical damage level, we can compute the maintenance intervals and/or the service life. Knowing the costs for each maintenance action per unit of material we can calculate the economic damage from air pollution.

Algorithm 2: *Calculating the economic damage from air pollution, using the analytic approach.*

1. Find/develop physical damage functions for all selected materials.
2. Determine materials service life, the critical damage level and maintenance measures/costs.
3. Use air quality information to calculate maintenance intervals and/or service life.
4. Build a material inventory with regard to accumulated physical damage for the area under consideration. Find out the amount of each material that is exposed to air pollutants.
5. Use the information gained in (3) and (4) to calculate the economic damage during a given period.

For a given material the economic damage can be calculated if the following information is available:

- Physical damage function.
- Critical damage level.
- Expected service life.
- Amount of material exposed to air pollutants.
- Taken maintenance measures and costs.

For a given material we can use an estimate of air quality to calculate the maintenance intervals and the actual service life depending upon the critical damage level. If we have information on the maintenance intervals, the calculation process is similar to that described by the four equations for the comparative approach.

3.3. Critical Damage Level and Lifetime of a Material

The critical damage level is that level of damage to a material at which maintenance actions are taken. Such a level depends on the use of the material, so that even for the same material different damage levels may exist. Paint may serve as an example: for private houseowners the critical damage level for painting their houses may depend on the appearance of the house, so that maintenance actions are taken, although the primary protective function of the paint has not been harmed. At the same time, a company may decide that the paint on their building still performs its purpose, although appearance has been adversely affected. Therefore, determining a critical damage level is a rather complicated process with great uncertainty.

To determine the critical damage level, McCarthy *et al.* (1984) developed an approach within their so-called "prevailing practice model". The authors introduce the term "lifetime", that is, "the time of exposure experienced until a critical damage level is reached at which action is taken and/or real costs are incurred". Using currently practised maintenance strategies, the authors determine a lifetime for each material (e.g., interval between application of paint, replacement of a material by a new one, etc.). They then select a suitable physical damage function. Application of this physical damage function to the previously determined lifetime delivers the critical damage level (consistent with the prevailing practice) for the material under consideration. This critical damage level usually is expressed in measurable units (see Section 3.1).

4. BUILDING ECONOMIC IMPACT MODELS FOR AIR POLLUTION DAMAGE

4.1. How to Choose Economically Important Materials

The number of materials that is exposed to atmospheric pollution is large; therefore, it is impossible to deal with them all. For the economic assessment of the impact of air pollutants on materials, one must choose only the important materials. The author considers a material to be important only if a significant amount is in use, if it is expensive to replace and if one can find a significant rate of damage by air pollutants. A selection of the important materials can be made from field studies of material damage and from an inventory of the materials being exposed.

McCarthy *et al.* (1984) considered the following combinations of pollutants and materials:

SO_2 – galvanized surfaces

SO_2 – painted surfaces (including coated steel)

O_3 – rubber products

TSP – soiling of surfaces

Stankunas *et al.* (1983) list the following economically significant materials exposed to pollution damage:

- Paint
- Structural metals
- Electrical components
- Fabrics
- Plastics and elastomers
- Non-metallic building materials
- Works of art and historic monuments

Salmon (1970) carried out a study on soiling and material damage associated with ambient particulate matter and SO_x concentrations. This study delivered much higher damage values than all subsequent studies for the US (for comparison, see Section 3.2, values calculated by Waddel (1971), Freeman (1979) and Yocum and Grappone (1977). Nevertheless, the ranking of the material damage delivers the economically important materials. All materials with a total accumulated damage greater than 1 billion (1970) US dollars are listed below:

- Paint
- Zinc
- Glass
- Cement and concrete
- Copper
- Nickel
- Aluminum
- Leather
- Paper

Materials with a SO_x-induced damage greater than 100 millions 1970 US dollars are listed below:

- Paint
- Zinc
- Fibers

- Cement and concrete
- Nickel
- Tin
- Aluminum
- Copper

Table 4.1 summarizes the results of Salmon (1970).

The list of economically important materials tends to vary with each author. The author of this report concludes that the following materials and structures should be considered:

- Paint
- Zinc (galvanized surfaces)
- Works of art and historic monuments
- Glass under the influence of soiling
- Non-ferrous metals, cement and concrete under the influence of particulate matter

4.2. How to Build Material inventories

For each economic assessment of material damage from air pollution, it is necessary to know the amount of exposed material ("material under risk"). On a highly aggregated level, such as a whole geographic region, it is possible to determine the quantity of material in place by accounting the net imports and the amount produced during a period equal to its service life. If one assumes that a specific amount of the material is exposed to air pollutants, the following strongly simplified equation delivers the amount of material under risk:

$$AMUR_T = \left[\int_{T-SL}^{T} (P(t)dt) + \int_{T-SL}^{T} (NI\ (t)dt) \right] * SAMEAP$$

where:

T	=	timepoint (e.g., 1.1.1980)
$AMUR_T$	=	amount of material under risk (e.g., physical unit) at timepoint T.
SL	=	service life (e.g., in years)
P(t)	=	production function for the material (e.g., physical unit). The integral denotes all material that is produced and in use.
SAMEAP	=	specific amount of material exposed to air pollutants

Table 4.1. Economic loss, materials damage attributed to ambient exposure to SO_x and particulate matter as estimated by Salmon (1970) (US EPA, 1981). Units: billions of 1970 US Dollars.

Material	SO_x	*PM*	*Total*
Paint	1.195	35.0	36.2
Zinc	0.778	24.0	24.8
Fibers[a]	0.358	0.5	0.9
Cement and concrete	0.316	5.4	5.7
Nickel	0.260	1.0	1.3
Tin	0.144	0.1	0.2
Aluminum	0.114	4.9	5.0
Copper	0.110	0.2	0.3
Carbon steel	0.054	<0.1	0.1
Building brick	0.024	0.1	0.1
Paper	0.023	1.1	1.1
Leather	0.021	2.5	2.5
Glass	<0.001	19.0	19.0
Building stone	0.018	0.1	0.1
Wood	0.018	<0.1	0.1
Brass and bronze	0.014	0.2	0.2
Magnesium	0.013	<0.1	<0.1
Alloy steel	0.009	<0.1	<0.1
Bituminous materials	0.002	<0.1	<0.1
Gray iron	0.002	<0.1	<0.1
Stainless steel	0.002	<0.1	<0.1
Clay pipe	0.001	<0.1	<0.1
Chromium	0.001	0.2	0.2
Malleable iron	0.001	<0.1	<0.1
Silver	0.001	<0.1	<0.1
Gold	0.001	<0.1	<0.1
Plastics	<0.001	4.7	4.7
Lead	<0.001	0.1	0.1
Molybdenum	<0.001	<0.1	<0.1
Rubber	<0.001	0.1	0.1
Refractory ceramics	<0.001	<0.1	<0.1
Carbon and graphite	<0.001	<0.1	<0.1
Totals[b]	3.8	99.2	102.7

[a] Combined effects of SO_x, O_3 and NO_x on cotton ($152 million), wool ($99 million), nylon ($38 million) and other synthetics ($69 million).

[b] Not additive, due to rounding.

(e.g., in percent)

NI(t) = function describing net imports (imports less exports)

On a mesoscale (district or country) and a local scale level (city) material inventories can be built up by sampling in selected areas, as described by Daum *et al.* (1986). They used a random sampling technique in four areas: Pittsburgh, Cincinnati, New Haven and Portland (Maine), whereby approximately 1100 buildings were included. Then they used two extrapolation strategies for calculating the amount of material under risk.

Their first extrapolation strategy assumed an average area per building, determined from the observations for each city under case study. Multiplication by the building counts information (obtained from the 1980 Census of Housing for residential structures and from tax records for non-residential buildings) estimated the area of materials exposed to air pollution. Secondly, for cities not being studied, the authors had to consider changes in the mix of materials in different parts of the country. For estimating these changes they used their experience gained by the four cities that were studied and the 1981 Department of Energy survey on residential energy consumption.

Other possibilities for building material inventories include extrapolation from land used by land use category, population densities and extrapolation from building counts, etc.

4.3. Suggestions for a Simple Model for Material Damage

This paper has to be seen in the light of the Transboundary Air Pollution Project. In the author's opinion, it is not yet possible to make an assessment of air pollution-induced material damage for Europe as a whole. Instead, countries should be regarded separately and a model describing material damage caused by air pollution should be composed of submodels describing each country. It is suggested that one start with building a model for one European country. The criterion for selecting a country should be the availability of data. After the implementation of this model on a computer is verified and hopefully validated, the model could be extended to other countries. The steps that have to be taken in designing such a restricted model are the following:

Step 1: The area of interest, e.g., one European country has to be selected.

Step 2: The materials that are of interest have to be selected (see Section 4.1). It is suggested to start with one material, e.g., zinc because its behaviour under the influence of air pollutants is well described in the literature. Later, the model can be extended to cover other materials.

Step 3: Because of the high uncertainty in the physical damage functions used in the analytical approach, the comparative approach (see Section 3.2) is preferred for calculating the economic impact from air pollution-induced material deterioration. According to the comparative approach, it is necessary to select atmospheric environment classes, such as rural or industrial. In a country that borders an ocean it is advisable to include a maritime atmospheric environment class to include the harmful influence of sea salts on materials.

Step 4: In this step, the model builder has to gather all information that is available on material service life, maintenance intervals and costs for replacement and maintenance. Those information have to be collected for each atmospheric environment class separately.

Step 5: Whichever modeling approach one chooses, the determination of the amount of exposed material has to be done. In the first approximation it can be done by accounting the net imports and the produced amount during a period equal to the service life of the material and by applying an exposure factor afterwards (see Section 4.2). After the amount of exposed material is calculated on a country basis, it has to be assigned to the different atmospheric environment classes. This may be done by extrapolation from statistics on land use, population densities and distribution of buildings and other structures. It also seems to be possible and reasonable to assign the material under consideration to several different atmospheric environment classes before applying different exposure factors for each class.

Step 6: In this step the economic damage that takes place in each atmospheric environment class is calculated by using equations (1) to (4) from Section 3.2(b).

The calculation process is expressed more formally below, on the assumption that one country, only one material and *k* atmospheric environment classes have been selected.

The amount of material exposed to air pollution (see Step 5 above) can be calculated by the following formula:

$$\mathrm{AMEAP}_T = \left[\int_{T-ASL}^{T} (P(t)\,dt) + \int_{T-ASL}^{T} (NI(t)dt) \right] * \mathrm{SAMEAP}$$

where:

T = timepoint (e.g., 1.1.1980)

AMEAP_T = amount of material exposed to air pollution (physical unit) at timepoint T.

ASL = average service life of the chosen material in the chosen country (e.g, years).

P(t) = is a production function. The integral denotes all material that is produced during the average service life of the selected material.

NI (t) = function describes net imports of the chosen

material (physical unit).
SAMEAP = specific amount of material exposed to air pollutants (e.g., percent).

The determination of the average service life is critical, because on a country-wide basis, it is not an average of the class specific service life

$$1/k * \sum_{i=1}^{k} SL_i$$

but a weighted average

$$\sum_{i=1}^{k} \left(SL_i * MIP_i / \sum_{j=1}^{k} MIP_j \right)$$

where MIP denotes the material in place and SL, the service life. The indices denote an atmospheric environment class. The weighted and the non-weighted averages deliver the same result if $SL = SL_i$ for all i. In the case that $SL \neq SL_i$ for at least one i and in the case that an average service life is not available from statistics, other methods have to be used to calculate the material in place or the amount of material exposed to air pollution.

The calculation of class specific exposed material is done by multiplication with a split vector that has to be determined:

$$AMEAP_i = AMEAP * AECSV_i$$

where:

$$\sum_{j=1}^{k} AECSV_j = 1 \text{ and } \epsilon_i \{1,\ldots,k\}$$

AMEAP = amount of material exposed to air pollution.
$AMEAP_i$ = amount of material exposed to air pollution by atmospheric environment class.
$AECSV_i$ = atmospheric environment class split vector (fraction exposed to specific atmosphere environment).

The calculation of the economic material damage from air pollution (Step 6) can be described as follows (see also equations (1) to (4) from Section 3.2 (b):

$$EMDAP_i = AMEAP_i * [(MCMAAM/LMI_i - SMCU) + (VPUM/SLU * (SLU-SL_i))]$$

where

$i \in \{1, ..., k\}$, and

$EMDAP_i$	= economic material damage from air pollution in class i.
$AMEAP_i$	= amount of material exposed to air pollution in class i.
MCMAAM	= maintenance costs per maintenance action and per amount of material.
LMI_i	= length of maintenance interval in class i.
SMCU	= specific maintenance costs in an unpolluted atmospheric environment.
VPUM	= value per unit of material.
SLU	= service life in an unpolluted atmospheric environment.
SL_i	= service life in class i.

5. RELIABILITY AND APPLICABILITY OF MODELS OF MATERIAL DAMAGE

At the present time, models of materials damage deliver poor results due to large uncertainties in input data and lack of knowledge about some of the damage mechanisms. Therefore, the output of these models must be regarded as approximate and it is advisable to use those model results only in qualitative way. Nevertheless, degradation by air pollution is an important issue in calculating the economic impact of air pollution. For that reason, ongoing research should be followed carefully. In the following sections, the reasons for the poor results of today's models will be discussed.

5.1. Errors Built into the Approach

(a) Analytic Approach

The presence of moisture plays an important role in material degradation. In physical damage functions this fact is taken into consideration by introducing a term called time-of-wetness. In Section 3.1, the reader will find a description how the time of wetness is usually determined. It is the author's opinion that this method for calculating the time of wetness is worthless, because it gives the impression that wetting is a uniform process. This is not in fact true: Sereda (Environment Canada, 1986) cites a report by Guttman (1982) in which the time of wetness depends strongly on the location of a material on a building or structure, as quoted in *Table 5.1*:

Because corrosion depends strongly on the time-of-wetness, one can assume that there will be great differences in the corrosion of one material at several different locations on the same building or structure. This means that damage functions including time-of-wetness (or moisture) will deliver unreliable results. This fact puts into question the use of the analytic approach for the assessment of

Table 5.1. Percentage of time-of-wetness on galvanized sheet metal, exterior walls and roof of a storage building (Trail, British Columbia, Canada).

West exposure	*South exposure*			*North exposure*		
Wall (midheight)	*Roof (overhang)*	*Wall (near roof overhang)*	*Wall (midheight)*	*Roof (overhang)*	*Wall (near roof overhang)*	*Wall (midheight)*
23.6	50.3	14.6	18.5	51.1	23.2	21.1

material damage. There are damage functions (see Section 3.1) that do not include the effect of moisture. These damage functions were obtained from correlations between material damage and air pollution concentrations and describe nothing more than a statistical correlation for a given location and an assumed level of humidity and are, therefore, useless for a large scale damage assessment.

In the author's opinion, the analytic approach that is used in different studies (e.g., Stankunas *et al.*, 1983; McCarthy *et al.*, 1984; Horst *et al.*, 1986) gives unreliable results. Stankunas *et al.* (1983) describe the possible error range as follows: "The usual practice when reporting costs based on the analytical approach is to give a range of error expected. Based on the accumulated uncertainties, the range of error often encompasses factors of ten or more. Sadly, the statements of uncertainties are often overlooked when people begin to use the calculated values for decision making".

(b) Comparative Approach

For the comparative approach it is necessary to find areas with similar atmospheric conditions for all factors except air pollution. In reality no such areas exist, so that the model builder has to deal with slight differences in the non-pollutant variables. These differences influence the empirical relationships that describe the interactions between air pollution and economic damage. Therefore, they may produce high uncertainty if only a small number of comparable areas can be selected.

Furthermore, a different usage of a material in another environment may lead to wrong results, e.g., if a material is too sensitive to high concentrations of air pollutants and therefore not used outdoors, longer maintenance intervals could give the wrong impression that the material becomes more resistant if the air pollution concentration is above a special threshold. Another problem in using the comparative approach is that the maintenance costs per maintenance action and per amount of material must be somehow determined.

(c) Estimates of the Material Under Risk

Both the analytic and the comparative approach suffer from difficulties in determining the amount of material that is suspective to air pollution. As far as is known, no country is building up building material inventories on a spatial basis. The only data on which one can rely are building counts and production statistics.

The transformation of these information into the amount of material under risk is a complicated process with large uncertainty. None of the methods described in Section 4.2 deliver an accurate result. The best result could possibly be obtained by combining the application of an exposure factor with sampling techniques. Nevertheless, the determination of the material under risk will introduce a large amount of uncertainty into the model.

5.2. Lack of Knowledge in the Field

There are several major areas in the field of materials damage in which knowledge is lacking. Firstly, natural atmospheric factors cause the same types of damages as air pollutants. Therefore, it is still unclear what portion of the observed material degradation can be attributed to the effects of air pollutants.

The physical damage functions that are described in Section 3.1 have to be seen as first approaches in describing material pollutant interactions. Many studies ignore the effects of NO_x, ozone and particulate matter, so that SO_2 is used to summarize all other pollution effects. This leads to an overestimation of the importance of sulfur for material damage from air pollution. The approaches that are used to describe the time of wetness are simple, so that all modeling approaches deliver very poor results when compared with reality. Dry deposition depends on a material-specific deposition velocity and on the air concentration of the pollutant. Most studies describing effects from dry deposition do not take into account that the concentration varies with the height and that therefore deposition rates will also vary according to the position on a building or structure.

In the author's opinion, recent studies have paid too little attention to temporal effects, such as accumulated damage versus introduction of new materials (e.g., paints) and new maintenance strategies. For a better understanding of the deterioration mechanisms it is necessary to undertake internationally coordinated research. Exposure programs with simultaneous measurement of all important factors that contribute to material degradation could help to improve our understanding. Such an exposure program started in September 1987 under the control of the ECE's "International Cooperative Programme on Effects of Air Pollution on Materials, Including Historical and Cultural Monuments". At a total of 39 sites within 13 European countries, four different groups of materials will be examined:

- Structural metals (steel, zinc, aluminum, copper, cast bronze)

- Stone
- Paint coatings
- Electrical contact materials

During the time of exposure the following parameters will be measured:

- Temperature and relative humidity (for calculating time-of-wetness)
- Solar radiation
- Sulfur dioxide concentration
- Nitrogen dioxide concentration
- Ozone concentration
- Amount, pH and conductivity of precipitation
- Concentration of sulfate, nitrate, chloride, ammomium and calcium ion in precipitation.

This program should result in a better understanding of the atmospheric deterioration process and as a consequence more reliable physical damage functions should be developed.

5.3. Local versus Distant Sources of Air Pollution

Local emissions play an important role in air pollution-induced atmospheric degradation. Generally, the distinction between local and remote sources is difficult. Sereda (Environment Canada, 1986) thinks that "it is reasonable to conclude that the summer values represent the 'background' SO_2 level mostly due to long-range transported pollution while the winter values represent the contribution of the local sources to the 'background' ".

Kucera (1986) points out the following: "Atmospheric corrosion is thus, at least in Scandinavia, a local effect mainly caused by a country's own emissions and not affected by long-distance transport of pollutants. The situation may, however, be different in densely populated areas of Western or Central Europe, where transport of pollutants over the national boundaries may also cause appreciable corrosion damage". As a proof for the above he gives the relationship shown in *Figure 5.1* and cites corrosion maps that were developed for selected areas in Europe. According to him very pronounced local variations of atmospheric corrosion that cannot be explained by wet deposition indicate an important influence of pollutants that are dry-deposited.

Yocom and Baer in Altshuller *et al.* (1983) state: "In urban areas where most materials are located, the atmospheric load from local sources tends to dominate over the smaller amount of pollutants arriving from remote upwind sources".

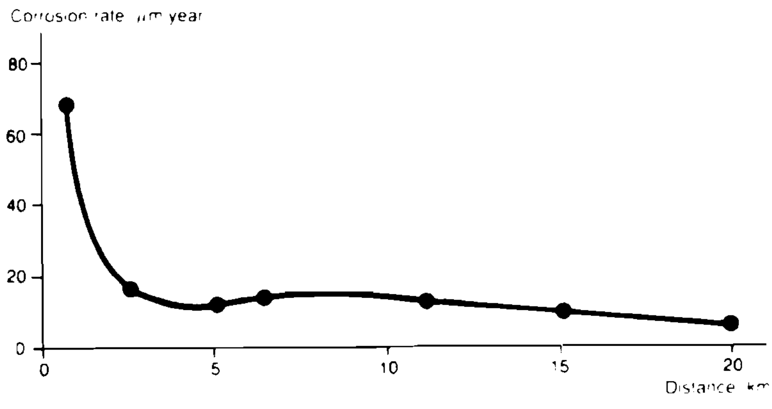

Figure 5.1. Corrosion rate of carbon steel as a function of the distance from the emission source – a chimney in Kvarntorp (Kucera, 1986).

These three statements indicate that in modeling air pollution-induced material degradation, local air pollution sources have to be regarded as well as remote sources.

6. CONCLUSIONS REGARDING INCORPORATION OF A MATERIAL DAMAGE SUBMODEL INTO THE RAINS MODEL

There exist at least three serious problems concerning the integration of air pollution-induced material degradation into the RAINS model.

First of all, the RAINS model and a possible submodel describing the impacts of air pollution-induced material degradation belong to two different classes of models. The author classifies the RAINS model into the class of predictive models. Predictive models are "based on known input and system structure. They are used to extrapolate developments or forecast changes" (Braat and Lierop, 1987). A submodel describing air pollution-induced material degradation would belong into the class of descriptive or exploratory models. According to Braat and Lierop (1987), these models are "intended for a preliminary analysis of the relevant problem or to give an initial overview which could provide a basis for more careful research of its structure relationship". The RAINS model is intended to be used in an international decision making process. The inclusion of a submodel that delivers poor and unreliable results may jeopardize this use because many people tend to judge the quality of a model by its weakest component.

Secondly, the RAINS model operates on both a spatial and temporal basis. All recent approaches in modeling the impact of air pollution-induced material degradation concentrate mainly on spatial determination of the damages, whereas the temporal dimension is neglected or strongly simplified. Integrating air pollution-induced material degradation into the RAINS model that operates on a time scale from 1960 to 2040 demands that the introduction of new materials and improved maintenance strategies must be modeled. Future changes of the amount of material in place can only be predicted if the economic development is known.

Thirdly, local emissions play an important role in air pollution-induced material degradation; consequently, the RAINS model that now deals with transboundary effects of air pollution would have to be extended to include local effects.

Because of the three above reasons, the author does not recommend that the economic impacts of air pollution-induced material degradation be included in the RAINS model. However, the author thinks that material degradation is an important issue in describing the impacts of air pollution. The assessment of economic damage from air pollution-induced material degradation presently relies more on speculation than on hard scientific facts. The author, therefore, suggests that the subject of material damage be approached in the following way.

The exposure and measurement program of the "International Cooperative Programme on Effects of Air Pollution on Materials, Including Historical and Cultural Monuments" under the control of the ECE (see Section 5.2) will lead to new physical damage functions for material degradation induced by air pollution. As soon as these new damage functions are available they could be introduced into the RAINS model as an indicator approach. The physical damage functions would be used to calculate the damage per amount of material for specific locations within Europe. The calculated damages for one material at different specific locations may serve as an indicator for the severity of air pollution-induced material degradation. For example, statements as the following would be possible: "Assuming the scenario x (e.g., 30% scenario) the physical damage to material m (e.g., zinc) at location 1 will be y% less than assuming scenario z (e.g., official energy pathway)." Even the modeling of this simple approach will require a great design effort because new variables such as amount, pH and conductivity of precipitation, local emissions, etc., must be introduced into the RAINS model. It is possible to use existing damage functions for the described indicator approach, but the author is of the opinion that these damage functions take too few factors into consideration so that the results are not reliable.

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