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Preface

Buildings and building materials industries play a significant role in affecting global energy and resource use. As with other sectors of society, the building industry has a history of reacting to environmental problems rather than anticipating and actively preventing potential problems.[1] Given the gravity of environmental degradation and the public's growing awareness and understanding, it is unlikely that it can remain passive. We face the difficult challenge of realigning the building industry with the dictates of sustainability while simultaneously operating within an existing social, political and economic context premised on growth.

The environmental agenda should bring about a profound change in the way we view and undertake the design of buildings. Addressing environmental issues will require design professionals to make difficult choices particularly since it will involve moving in to areas of knowledge which are relatively uncharted. The design community currently has very little sound advice or information for considering environmental issues in an industry driven by immediate costs and where producers are slow to take the lead in introducing necessary change However, we can anticipate a rapid increase in information on a broad range of environmental aspects of materials and design strategies. As this information becomes available and the environmental linkages more clear, design professionals will be able to respond by adopting designs, methods and materials which reduce the environmental impact of buildings.

The building industry is fragmented and, compared with others, invests the least amount of funds into on-going research to develop new technologies and practices. Addressing the environmental agenda will require a re-examination of current methods of building materials production and the development of new environmentally responsible technologies and building design and construction practices. Research is increasing rapidly on a broad range of environmental aspects of buildings. It is currently uncoordinated and their is an urgent need to establish a consistent set of definitions and methodologies to facilitate dialogue and exchange between researchers.

An intensive two-day working session involving leading international researchers currently examining the environmental consequences of building and representatives from European and North American Architectural Associations was held at Queens' College, Cambridge University, September 27-29th 1992. The meeting had two objectives. First, to explore and define research protocols for assessing the life-cycle analysis of the environmental impacts of buildings and second, to examine what design 'tools' would be most appropriate to assist architects in making more informed environmental choices.

This volume of the proceedings records the papers and discussion related to the research component of the meeting. It is hoped that these proceedings will contribute to the current debate on life-cycle analysis techniques as they relate to buildings.

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[1] Lorch, R., (1990) 'Towards Green Buildings,' *Royal Institute of British Architects Journal*, February 1990, pp58-59

Contents

Part One: Presentations

Part Two: Workshop Discussions

PART ONE: PAPER PRESENTATIONS

Appropriated Carrying Capacity: Ecological Footprints and the Built Environment by William Rees

External Costs and a New Tool for Hybrid Analysis in Life Cycle Costing by Olav Hoymeyer

The Integration of Environmental Impact Assessment Methods in the Planning Process of Buildings by Niklaus Kohler

Methodological Principles for Life Cycle Impact Assessment (LCIA) of Buildings by Thomas Lützkendorf

Environmental Evaluation Methods Based on Energy and Material Flows as Applied to Buildings by Yvan Leuridan and Niklaus Kohler

A Hierarchical Model for Building Costs by John R. Bedell and Niklaus Kohler

Appropriated Carrying Capacity: Ecological Footprints and the Built Environment

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1.0 Introducing the Dialectic

This paper is inspired by the tension between two competing visions of global economic reality. One of these, the "expansionist worldview" is the dominant social paradigm (Taylor 1991; Milbrath 1989). Its confident logic shapes the macroeconomic policy of the world's major countries and provides the economic rationale driving mainstream international development efforts today. The other vision is an "ecological worldview." Not fully formed and inherently less confident, this perspective has to date been little more than a minor if increasingly persistent irritant snapping at the heels of its dominant rival.

Nothing is closer to the centre of the tension than the question of whether the ecosphere imposes practical constraints on the material activities of humankind. Lawrence Summers, chief economist of the World Bank and among the most outspoken engineers of the expansionist vision was recently quoted as saying: "There are no........limits to carrying capacity of the Earth that are likely to bind at any time in the foreseeable future. There isn't a risk of an apocalypse due to global warming or anything else. The idea that the world is headed over an abyss is profoundly wrong. The idea that we should put limits on growth because of some natural limit is a profound error" (cited in George 1992). By contrast, the ecological perspective holds that the "profound error" resides wholly in Summers' statement. As Garrett Hardin most succinctly put it, "carrying capacity is the fundamental basis for demographic accounting" (Hardin 1991:54).

The dominant perspective, as articulated by the World Bank (World Bank 1992) and the 1987 *UN World Commission on Environment and Development* (WVED 1987), acknowledges the ecological damage caused by development. However, it sees developing world problems such as soil erosion, and the lack of clean water and sewers (failing infrastructure generally) as the most pressing issues and poverty as the cause. It follows that to fix the environment we have to fix poverty and "the cure for poverty is growth" (*The Economist* 1992). Indeed, the *Brundtland Commission* effectively equated sustainable development with "more rapid economic growth in both industrial and developing countries" and observed that "a five to tenfold increase in world industrial output can be anticipated by the time world population stabilizes some time in the next century" (WCED 1987:213.)[1] However, by failing to assess the biophysical feasibility of this prescription, the Commission put carrying capacity at centre stage in the evolving world development debate.

This paper takes up the argument that an ecological perspective on carrying capacity is essential to any rational approach to the global development conundrum. There are three simple reasons for this. First, despite our technological wizardry and assumed mastery over the environment, humankind remains a creature of the exosphere existing in a state of

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[1] While this may seem like an extraordinary rate of expansion, it implies an average annual growth rotate in the vicinity of only 3.5 - 4.5% over the next 50 years. Growth in this range has already produced a near five-fold increase in world economic output since the Second World War.

obligate dependency on many products and processes of nature (Rees 1990). On the simplest level, our ecological relationships to the rest of ecosphere are indistinguishable from those of the millions of other species with which we share the planet. Like all other organisms, we survive and grow by extracting energy and materials from those ecosystems of which we are a part. Like all other organisms, we "consume" theses resources before returning them in altered form to the ecosphere. Second, the five-fold increase in the human economy in the post war period has begun to induce ecological change on a global scale which simply can no longer be ignored. Finally, orthodox economic analysis is so abstracted from biophysical reality that its ability to detect, let alone advise on, critical dimensions of carrying capacity is severely compromised.

2.0 Economics as Errant Human Ecology

Ecology is often defined simply as the study of the relationships between organisms and their environments. A more insightful definition is "the experimental analysis of distribution and abundance" [of plants and animals] (Krebs 1972). However, from an ecological economics perspective, ecology is best defined as the scientific analysis of the flows of energy and material resources through ecosystems and of the competitive and cooperative mechanisms that have evolved for the allocation of resources among different species. This definition stresses the homology of ecology and economics, the latter commonly being defined as the scientific study of the efficient allocation of scarce resources (energy and material) among competing uses in human society. From this perspective, ecology and economics are seen to share not only the same semantic roots, but also the same substantive focus. In fact, it could logically be argued that economics is really human ecology.

Or rather, it should be. The problem is that mainstream economics has deviated markedly from the theoretical foundation that still support its sister discipline. The material ecology of *other* species has roots in the chemical and thermodynamics laws that are the universal regulators of all transformations of energy and matter in the organic world. Economics, by contrast, had abandoned its classical organic roots by the end of the 19th Century. Neoclassical economics (which has recently enjoyed a remarkably uncritical renaissance the world over) is firmly based on methods and concepts borrowed from Newtonian analytic mechanics.

The result of this divergence is dominant economic paradigm which "lacks any representation of the materials, energy sources, physical structures, and time dependent processes basic to an ecological approach" (Christensen 1991). Prevailing theory therefore produces analytic models based on reductionist and deterministic assumptions about resources, people, firms, and technology that bear little relationship to their counterparts in the real world (Christensen 1991). In short, mainstream economists inevitably ignore critical elements of ecological theory, having sought refuge in the more theoretically tractable but environmentally less relevant realm of mechanical physics.

We are therefore confronted with a double irony in applied human ecology. Conventional economists, arguably the most influential of human ecologists, are also the most theoretically errant. Meanwhile, ecologists, who start from appropriate theory, have all but ignored humankind. This severely limits the contribution of both disciplines to resolving the global ecological crisis.[2]

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[2] This critique is not aimed at entire disciplines but rather at the particular "brand" of economics that currently dominates the development policy arena and at mainstream academic ecology. Many economists do work with

2.1 Will the Myth Most Closely Approximating Reality Please Stand Up

Four important consequences of this theoretical dichotomy will serve to illustrate the dilemma:

☐ Traditional economic models often represent the economy as essentially separate from and independent of "the environment." By contrast, an ecological economic perspective would see the human economy as an inextricably integrated, completely contained, and wholly dependent subset of the ecosphere.

☐ Economic theory treats capital and individual imputs to production as inherently productive, ignoring both their physical connectedness to the ecosphere and the functional properties of exploited ecosystems. By contrast, systems ecology emphasizes connectivity, particularly material and energy flows in relation to the functional integrity of ecosystems.

☐ According to neoclassical theory, resource depletion is not a fundamental problem - rising prices for scarce resources automatically leads to conservation and the search for substitutes (Barnett and Morse 1963; Dasgupta and Heal 1979). Conventional wisdom holds that substitution through technological progress has been more than sufficient to overcome emerging resource scarcities (Victor 1991). This lead economist and Nobel Laureate Robert Solow to argue that if resources are highly substitutable "......the world can, in effect, get along without natural resources" (Solow 1974).[3] By contrast, ecological analysis reveals that humankind remains in a state of obligate dependency on numerous biophysical goods and services with great positive economic value but for which there are no markets nor feasible substitutes (e.g., the ozone layer). In the absence of markets, the already questionable scarcity indicators of conventional economics - prices, costs, and profits - fail absolutely.

☐ Finally, the mechanical metaphor describes an economy which is self-regulating and self-sustaining in which complete reversibility is the general rule (Georgescu - Roegen 1975). From this perspective, the starting point for economic analysis is the circular flow of exchange value (Daly 1989). By contrast, thermodynamic reality means the economy is sustained entirely by low entropy energy and matter produced "externally" by ecosystem and biophysical processes. Thus all economic production is actually consumption - the ecologically relevant material and energy flows through the economy are unidirectional and irreversible (Rees 1990).

This last factor is crucial to any attempt to account for the ecological effects of any economic process. Without reference to entropic throughput "it is virtually impossible to relate the economy to the environment," yet the concept is "[all but] absent form economics today" (Daly 1989).

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dynamic, ecologically realistic, multiple equilibrium models and many systems ecologists do focus similar tools on the impacts of human beings.

[3] However, Solow (1991) acknowledges that "there is no reason to believe in a doctrinaire way" that "the goal . . . of sustainability can be left entirely to the market.

3.0 Natural Capital and "Living on the Interest"

Some economists have accepted the argument that sustainability[4] requires the conservation of certain biophysical entities and processes. These 'resources" may have immeasurable economic value, yet are often not even recognized as imputs to the economy. They maintain the life-support functions of the ecosphere, the risks associated with their depletion are unacceptable, and there are no technological substitutes. For these reasons, "*conserving what there is* could be a sound risk-averse strategy" (Pearce *et al.*, 1990:7 [emphasis added]).

Ecological economists have begun to regard such assets as a special class of "natural capital," and are exploring various interpretations of a "constant capital stock" condition for sustainability (Costanza and Daly 1990, Daly 1989, Pearce and Turner 1990, Pearce *et al.* 1989, 1990; Pezzey 1989; Rees 1982).[5] The following interpretation is most relevant to the concept of carrying capacity:

Each generation should inherit an adequate stock of natural assets alone no less than the stock of such assets inherited by the previous generation.[6]

This interpretation reflects basic ecological principles, particularly the multifunctionality of biological resources. It corresponds to Daly's (1989) definition of "strong sustainablility" which recognizes that manufactured and natural capital "are really not substitutes but complements in most production functions" (Daly 1989:22). The constant natural stocks criterion also implies that, for the foreseeable future, humankind must learn to live on the annual flows - the "interest" - generated by remaining stocks of natural capital (Rees 1990). It is therefore related to Hicksian (or "sustainable") income, the level of consumption that can be maintained from one period to the next without reducing wealth (productive capital). Of course, if populations or material standards increase, natural capital stocks would have to be enhanced to satisfy demand (*Figure 1*).

Determining what mix and just how much ecosystems capital to preserve remains a major problem. Neoclassical theory suggests that "development: should proceed only to the point at which the marginal costs of natural capital depletion (diminished ecological services) begin to exceed the marginal benefits produced (additional jobs and income). However, this assumes that we can identify, quantify, and price all relevant life support functions and that any change in the properties of ecosystems under stress will be smoothly continuous (i.e., predictable) and reversible. Unfortunately, neither assumption holds (Rees 1991, 1992).[7]

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[4] Sustainable development is defined as positive socioeconomic change that does not undermine the ecological systems or basic social infrastructure upon which society is dependent. "Development" implies qualitative betterment or improvement, which may or may not involve material growth within ecosystems constraints. For political viability, specific measures for sustainability require the support of the people through their governments, their social institutions, and their private activities (Rees 1989).

[5] The idea of inviolable resources stocks is anathema to conventional economists who argue that resources should be used to generate more wealth, including more productive substitutes for the original resource.

[6] "Natural assets" encompasses not only material resources (e.g., petroleum, the ozone layer, forests, soils) but also process resources (e.g., waste assimilation, photosynthesis, soils formation). It also includes renewable as well as exhaustible resources. Our emphasis here is on the need to maintain adequate stocks of renewable biophysical resources. (Note that the depletion of nonrenewables could be compensated for through investment in renewable assets.)

[7] Economists regard cost-benefit analysis as the definitive tool in environmental decision making. However, " . . . difficulties with missing data, uncertainty, and too little time and resources for an exhaustive analysis combine with the theoretical difficulties to make ineffectual any serious claim that an applies study produces an optimal or theoretically justified outcome" (Lave and Gruenspecht 1991).

This approach also leaves unanswered the questions of substitutability within natural capital and how global natural capital requirements should be allocated geographically. Here, too, conventional theory fails - prevailing economic rationality is indifferent to equity considerations or place, often reducing the whole economy to a single statistic. Thus, in the specification of optimal stocks, monetary analysis provides but a single critical insight: beyond some theoretical optimum, material growth is actually "anti-economic growth" that ultimately "makes us poorer rather than richer (Daly 1990:118).[8]

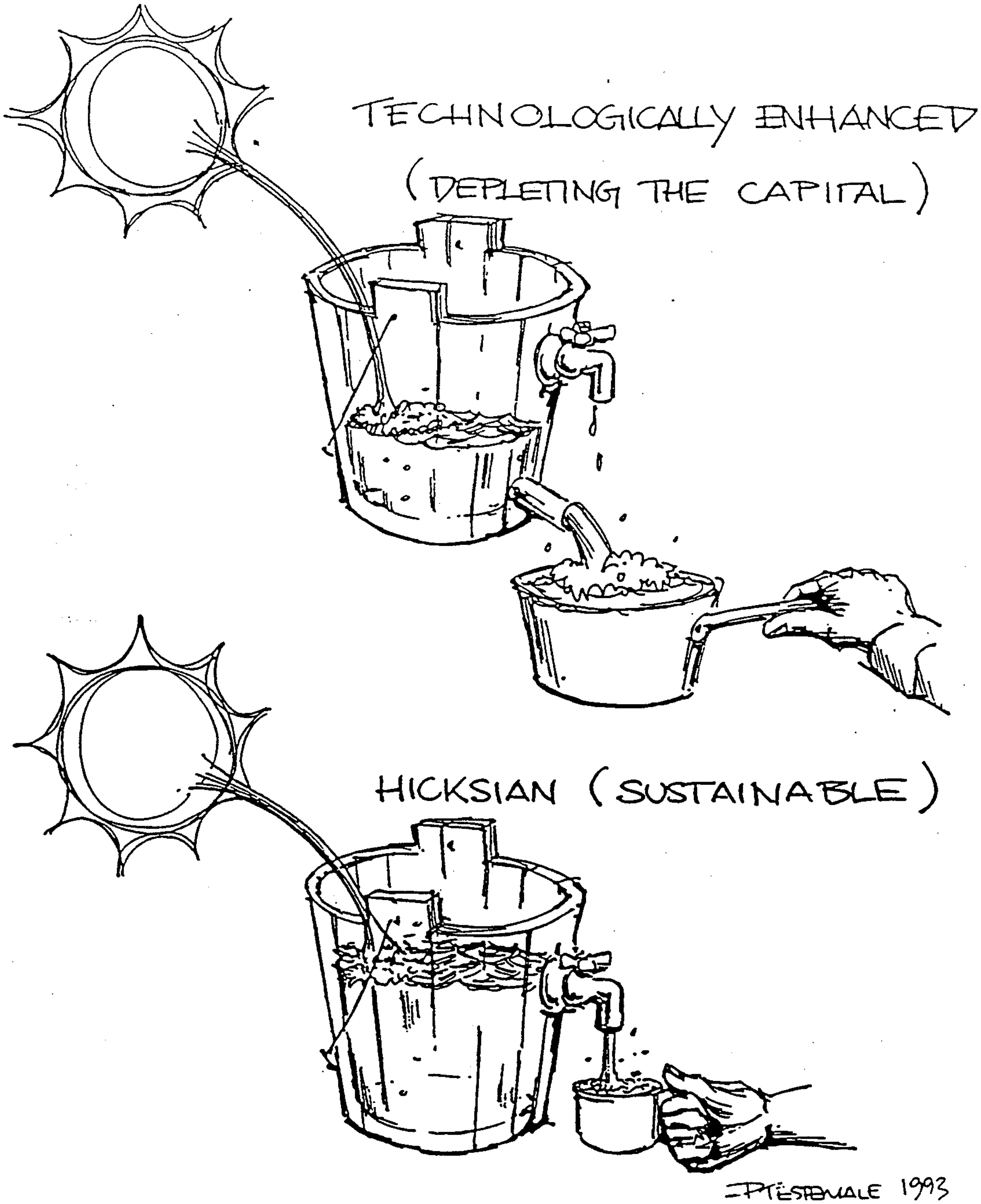

Figure 1: Technology has progressively enabled humankind to exploit natural capital far beyond sustainable levels

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[8] In any event, persistently negative ecological trends indicate that the world economy may already have passed the global optimum.

4.0 Ecological Footprints and Appropriated Carrying Capacity

This section describes an alternative empirical approach to the optimal stocks question. We derive estimates of the actual physical stocks of natural capital necessary to sustain a given human population and compare this to carrying capacity of the population's home territory. This ecological approach avoids pricing problems altogether. While arguably central to ecology/economy integration, the ideas explored here are largely ignored in the mainstream policy arena.

In fact, many economists have totally rejected the concept of ecological carrying capacity (and remain unaware of the natural capital concept). Some do acknowledge that certain countries may face carrying capacity limitations ".....even if the rest of the world is poised for sustainable growth indefinitely without significant environmental or resource constraints" (Muscat 1985:6). However, a 1986 economists' committee report on population growth and economic development for the US National Research Council (1986) is more typical: ".... neither the word *nor the concept* of 'carrying capacity' played a role" (Hardin 1991:54, original emphasis). The conventional wisdom seems to be that "the carrying capacity of the planet in terms of food (and other raw materials) appears to be well in excess of any likely human population magnitudes or the next century" (Muscat 1985:6).

Ecological analysis, however, reveals dimensions of the human population-resources problem that are invisible to conventional economic rationality. For example, economists see cities as loci for intense socioeconomic interaction among individual and firms, and as engines of *production* and national economic growth. By contrast, ecology highlights the extended relationships among concentrated human populations, patterns of *consumption*, and the inward flows of usable energy and material. The latter approach shows that the common perception of the city as specific geographic location is illusory - urban areas can survive only if reliable supplies of low entropy material resources and surplus waste absorption capacity is being produced elsewhere in the ecosphere (Overby 1985). From the ecological perspective, this absolute dependency underscores the fact that the city is mostly not where it appears to be!

4.1 Carrying Capacity Revisited

Ecologists define "carrying capacity" as the population of a given species that be supported indefinitely in a defined habitat without permanently damaging the ecosystem upon which it is dependent. However, because of our culturally variable technology, different consumption patterns, and trade, a simple head-count cannot apply to human beings. Human carrying capacity must be interpreted as the maximum rate of resource consumption and waste discharge that can be sustained indefinitely without progressively impairing the functional integrity and productivity of relevant ecosystems *wherever the latter may be*. The corresponding human population is a function of *per capita* rates of material consumption and waste output (i.e., net productivity divided by *per capita* demand) (Rees 1990). this formulation is a simple restatement of Hardin's (1991) "Third Law of Human Ecology:" (Total human impact on the ecoshpere) = (Population) x (*Per capita* impact). Early versions of this law date from Ehrlich and Holdren who also recognized that human impact is a product of population, affluence (consumption), and technology: I = PAT (Ehrlich and Holdren 1971; Holdren and Ehrlich 1974). The important point here is that a given rate of resource throughput can support fewer people well or more at subsistence levels.

Now, the inverse of traditional carrying capacity provides an estimate of natural capital requirements in terms of productive landscape. Rather than asking what population a particular region can support sustainably, the question becomes: How much productive land and water area in various ecosystems is required to support the region's population indefinitely at current consumption levels?

Our preliminary data for industrial cities suggest that *per capita* primary consumption of food, wood products, fuel, waste-processing capacity, etc., co-opts on a continuous basis several hectares of productive ecosystem, the exact amount depending on the average levels of consumption (i.e., material throughput). This average *per capita* index can be used to estimate the total area required to maintain any given population. We call this aggregate area the relevant community's total "ecological footprint" on the Earth (Rees 1992; *Figure* 2).

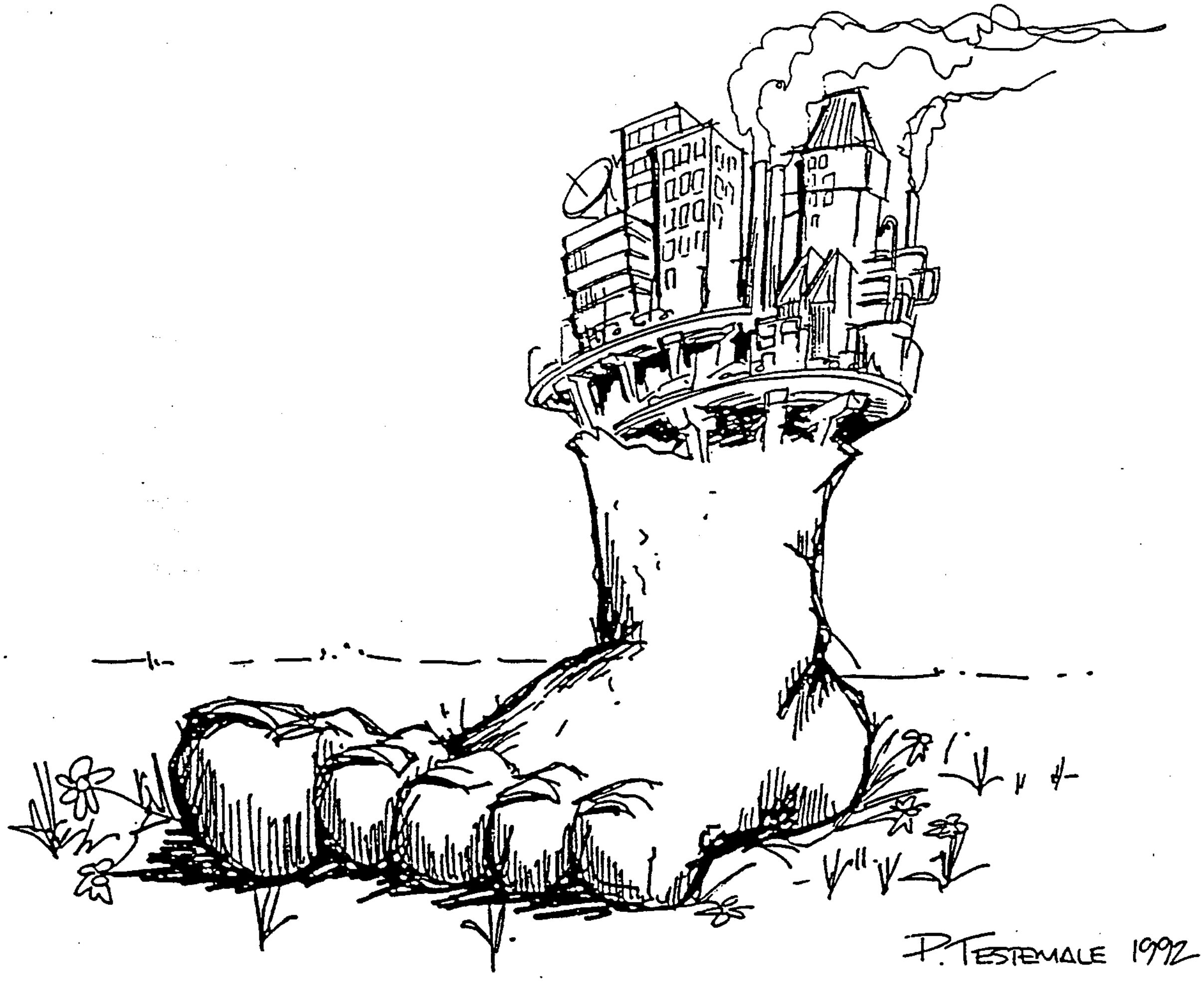

Figure 2: The ecological footprints of individual regions are much larger than the land areas they physically occupy.

This approach reveals that the land "consumed" by urban regions is typically at least an order of magnitude greater than that contained within the usual political boundaries or the associated built-up area. However brilliant its economic star, every city is an entropic black hoe drawing on the concentrated material resources and low-entropy production of a vast and scattered hinterland many times the size of the city itself. Borrowing from Vitousek *et al.*,

(1986) we say that high density settlements "appropriate" carrying capacity from all over the globe, as well as from the past and the future (Wackernagel 1991).

The Vancouver-Lower Fraser Valley Region of British Columbia, Canada serves as an example. For simplicity's sake consider the region's ecological use of forested and arable land for domestic food, forest products, and fossil energy consumption alone: assuming an average Canadian diet and current management practices, 1.1 ha of land *per capita* is required for food production, 0.5 has for forest products, and 3.5 ha would be required to produce the biomass energy (ethanol) equivalent of current *per capita* fossil energy consumption. (Alternatively, a comparable area of temperate forest is required exclusively to assimilate current *per capita* CO_2 emissions). Thus, to support just their food and fossil fuel consumption, the region's 1.7 million people require, conservatively, 8.7 million ha of land in continuous production. The valley, however, is only about 400,000 ha. our regional population therefore "imports" the productive capacity of at least 22 times as much land to support its consumer lifestyles as it actually occupies (*Figure 3*). At about 425 people/km^2, the population density of the valley is comparable to that of the Netherlands (442 people/km^2).

Even with generally lower *per capita* consumption, European countries live far beyond their ecological means. For example, our rough estimates suggest that the Netherlands' population consumes the output of at east 14 times as much productive land as is contained within its own political boundaries (approximately 110, 000 km^2 for food and forestry products and 360,00 km^2 for energy) (using data from WRI 1992).[9]

These data allow us to introduce two new concepts to the sustainability debate. First, they reveal that all urban industrial regions and some entire industrial countries are running massive ecological deficits. These regions are "spending " vastly more ecological income (including significant capital component) than they are capable of generating within their own boundaries. In effect, the excess flows represent an accumulating but unaccounted ecological debt, much of it "owed" to other countries which are in ecological surplus. The rest is drawn from the global commons.

The second concept is based on comparing the geographic area actually occupied by a given region or country to its ecological footprint as defined above. For those regions / countries whose ecological footprints are larger than their physical areas, the difference represents a "sustainability gap." This is a measure of the amount by which the ecological footprint of such regions would have to be reduced in order for them to live on their internally generated ecological income (plus, of course, an equitable share of the global commons).

Clearly, the sustainability gaps of industrial regions must necessarily be made up by flows from resource hinterlands. Indeed, whole countries could theoretically remain dependent on trade flows indefinitely provided the necessary surpluses exist somewhere else. However, the important point is that not all countries on a finite planet can run such ecological deficits.

Global sustainability requires that for every region running an ecological deficit, there must be equivalent surplus carrying capacity elsewhere on the planet. In short, the aggregate ecological footprint of the world economy cannot for long exceed the size of the globe - there can be no "sustainability gap" between the ecosphere and the human enterprise as a whole.

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[9] The Reijksinstituut voor Volksgezondheid en Milieuhygiene in the Netherlands suggests that for food production alone that country appropriates 170,000 to 240,000 km^2 of agricultural land (Meadows *et al.* 1992).

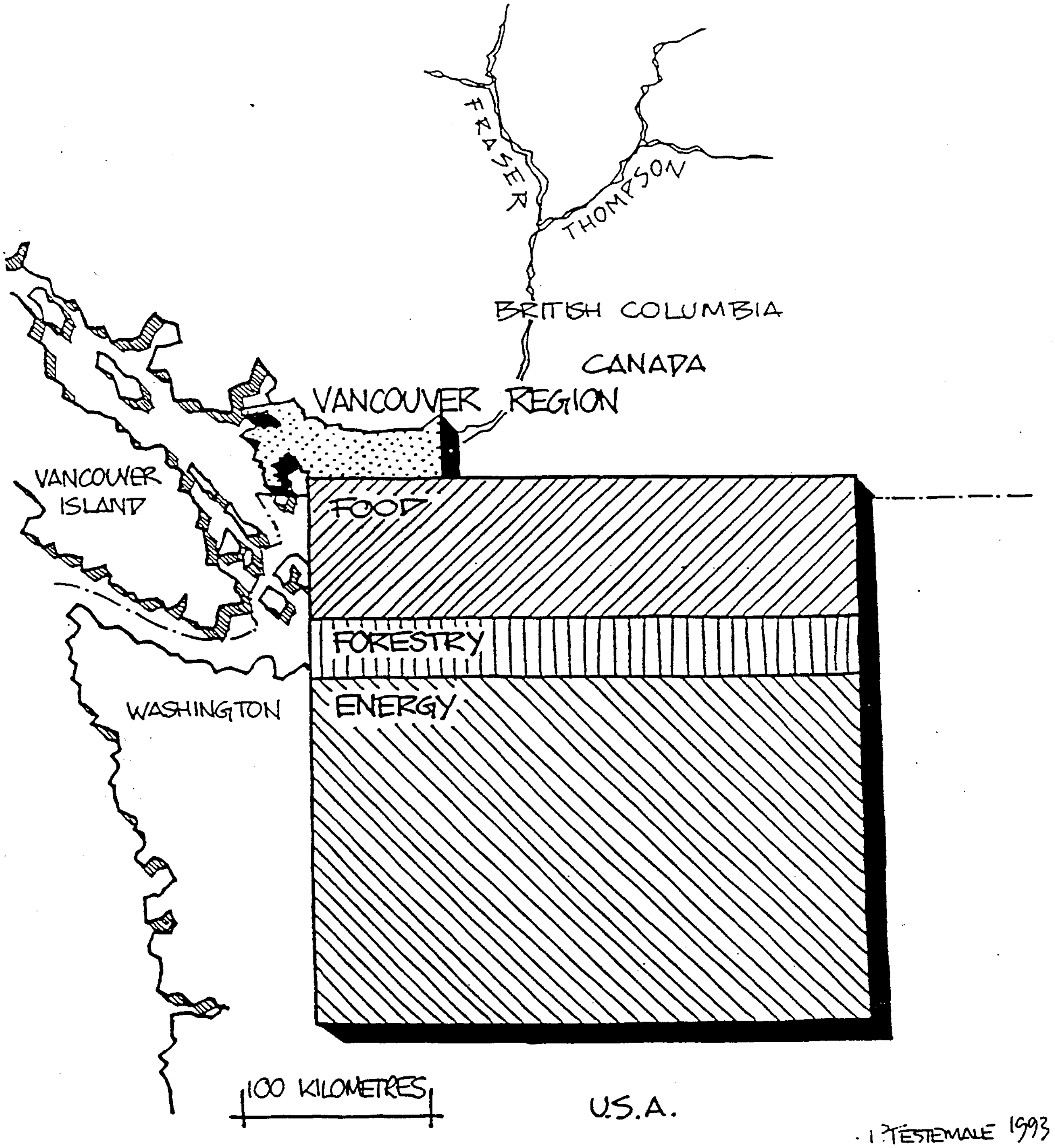

Figure 3: The Vancouver-Lower Fraser Valley Region appropriates from nature the ecological production of an area 22 times larger than the Lower Fraser Valley itself.

This analysis underscores the need in planning, urban design, engineering, and architecture to contribute to reducing the existing ecological footprints and deficits of the industrial countries. If the developing countries are ever to achieve a satisfactory material standard of living, the people of the developed world are going to have to create sufficient ecological space to allow for the necessary material growth in the Third World.

It is worth noting once again that prevailing development models ignore such carrying capacity consideration and take no consideration of ecological accounts. The explicit assumption is that all countries will be able to follow the development path of the industrialized world to more or less comparable material standards of living with impunity. This approach to sustainability assumes continuing unconstrained economic growth in both the developed and developing world facilitated by more liberalized trade, and both economic and technological efficiency gains. In short, it assumes a world "in which carrying capacity is infinitely expandable" (Daly, 1986)

4.2 The Ecological Footprint of the Built Environment

Human-made structures, including buildings and urban infrastructure, are constructed using energy and material resources appropriated from nature's flows or (in the case of non-renewable resources) directly from stocks. In addition, the operation and maintenance of buildings makes continuing demands both on sources of low entropy natural capital (exergy)[10] and on the waste assimilation functions of the ecosphere. This means that individual buildings make ecological footprints on the Earth which are much larger than the physical areas occupied by their plan foundations. It also implies that energy- and material efficient design and construction may contribute significantly to reducing the ecological deficits incurred by our built environments.

In contemplating efficiency gains it is important to work toward maximizing second law efficiency. This is defined as the ratio between the available energy (exergy) required to do a particular job and the amount of available energy actually used to do the job (Simpson and Kay, no date). By contrast, much current technology emphasizes first law efficiency, the ratio of energy output to energy input.

Electric baseboard heaters serve as an example of the general approach. By standard first law analysis, baseboard heaters are usually cited to be 90% or more efficient: that is, over 90% of the electrical energy is converted to heat energy. However, electric baseboard heaters use very high-grade energy to perform a task that actually requires very little work - space heating in homes and offices. In effect, most of the available energy in the electricity is wasted in its conversion to low grade heat (Simpson and Kay, no date), Ross and Williams (1976: 31) estimate the second law efficiency of these heaters at only 2.5%, very much less than the usual first law estimates.

The same task might be performed by a heat pump at considerable savings. A heat pump is a device that can move heat energy from one place to another - for example, from the ground outside a building to the air inside. It requires less energy to "pump" low grade heat even against a thermal gradient than it does to provide the same heating service through the thermal degradation of electricity of a baseboard heater. Heat pumps may have a second law efficiency of 9% and are sometimes reported to be up to 270% efficiency using first law analysis! (AIP 1975: 49-50, cited by Simpson and Kay, no date). Since energy land (for CO_2 assimilation) is an important component of industrial countries' ecological footprints, savings on this scale have the potential to make a considerable contribution to closing the sustainability gap.

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[10] Low-entropy energy / matter, negentropy, unbound energy, available energy, and exergy are often used synonymously in the literature. "Exergy" is more commonly used in Europe. All terms refer to the potential of high-grade energy to do useful work. This potential is a measure of the difference between a high-grade energy source and low-grade background conditions. In the case of matter (e.g., mineral deposits) it measures concentration relative to background.

4.2.1 Efficiency: A Cautionary Note[11]

Indeed, many economists and environmentalists believe that advances in technological efficiency is a potential panacea for the global ecological crisis. This follows Buckminster Fuller's reasoning of "doing more with less" and contains the hidden assumption that Efficiency gains automatically lead to resource savings and reduced consumption. As logical as this might seem, increasing the output: input ratio (in either first law or second law terms) does not necessarily result in lower resource use. On the contrary, technological efficiency may actually lead to increased net consumption of resources.

This should not come as a surprise. Over one hundred years ago in The Coal Question, Jevons pointed out that "it is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth" (1865: 140). He states that inefficient machinery consumes little because the rate of consumption is too high and hence uneconomical (1865: 143). By contrast, "the reduction of the consumption of coal, per ton of iron, to less than one-third of its former amount, was followed, in Scotland, by a tenfold increase in total consumption, between the years 1830 and 1863, not to speak of the indirect effect of cheap iron in accelerating other coal-consuming branches of industry" (1865: 154).

Many mechanisms work to produce these unexpected results, including the price and income effects of technological savings. Improved energy or material efficiency may enable firms to raise wages, increase dividends, or lower prices, all of which may lead to increased net consumption by workers, shareholders, or customers. Similarly, technology-induced savings by individuals are usually redirected to other forms of consumption, canceling some of the initial gain. As Hannon (1975: 99) points out, "the [environmentally conscious] traveler who [switches] from urban bus to bicycle would save energy (and dollars) at the rate of 51,000 Btu pr dollar. If he were not careful to spend his dollar savings on an item of personal consumption which had an energy intensity greater than 51,000 Btu pr dollar then his shift to bicycle would bane been in vain." These income and price effects are summarized as the "rebound effect" by economists (Jaccard 1991: 2).

Partially as a result of the rebound effect, "continuing growth in material consumption - the number of cars and air conditioners, the amount of paper used, and the like - will eventually overwhelm gains from efficiency, causing total resource use (and all the corresponding environmental damage) to rise" (Brown *et al.*, 1991). For example, U.S. data show that despite the increasing fuel efficiency of cars, aggregate fuel consumption continues to rise. Similarly, The Ecologist observes that although energy intensity [joules/$GNP] improved by 23 percent in OECD countries between 1973 and 1987, total annual energy consumption by these countries increased by 15 percent between 1975 and 1989 (1992: 168).

In summary, to the extent that efficiency gains contribute to enhanced corporate or personal savings (or profitability) they may contribute also to accelerated growth, increased demand for resources, and upward-trending expectations or returns to capital. This tendency is enhanced by competition which stimulates efficiency-oriented innovation. Micro-economic reality demands that efficiency gains be used to short-term economic advantage but soon the new technologies are in common use throughout the entire industry helping to stimulate additional growth.

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[11] Abstracted and revised from Wackernagel and Rees (1992).

Ironically, then, it is precisely economic gains from improved technical efficiency that increase the rate of entropic throughput. Far from conserving natural capital, this leads to its competitively accelerated depletion. The ecological footprint of the economy expands rather than contracts. To the extent that efficiency gains in the building sciences contribute to reduced capital costs, or lower long-term operating expenses for building owners and occupants, such gains will undoubtedly contribute to the general trend. To be effective in reducing ecological impacts, efficiency savings must be accompanied by increased energy and material costs, perhaps in the form of new depletion taxes. In a globally interlinked economy, the question is: Can we afford cost-saving energy efficiency? The answer may be "yes" only if efficiency gains are taxed away or otherwise removed from further economic circulation.

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External Costs and a New Tool for Hybrid Analysis in Life Cycle Costing

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This paper introduces the concept of social or external costs as a valuation approach in life cycle costing. In addition it reports on a new methodological tool for the hybrid analysis of economic activities in life cycle costing. The German input-output tables have been augmented by annual physical energy and emission coefficient matrices. If this tool is combined with process analysis for the first and most important steps of production, it allows to take into account all further levels of intermediate production involved. If the physical results of the hybrid analysis (emissions of pollutants or demand for energy) are combined with the costing approached developed for the evaluation of external or social costs, it is possible to move a substantial step further into the direction of true total life-cycle costing.

1.0 The social or external costs of economic activities

As Kohler (1991, p. 4) points out one of the major shortcomings of conventional life cycle costing is the failure to include costs which are not reflected by market prices or the internal cost calculations of the different economic agents. Costs like environmental or health damage costs resulting from economic activities are not taken into account. The most direct way to overcome this deficiency is the attempt to monetize these cost elements and to include them in life cycle costing. In the following a short introduction to the monetization of social or external costs is given for the example of different ways to produce electricity. The general approach can be easily extended to building activities just as well.

1.1 Introduction to the problem

In a market economy, the basic economic problem of allocating scarce resources to competing uses is solved through the market mechanism based on the market prices of the resources. A precondition for the optimal functioning of this allocation process is that the market prices reflect all costs involved in production. If this situation is assured, the microeconomic calculations of the economic agents involved may lead to a macroeconomic optimum of the allocation process for society. If, however, substantial costs of the production process are not reflected in the market prices because such costs are passed on to third parties not involved as consumers or producers of a product (in the instance of external or social costs), the market mechanism cannot secure an optimal macroeconomic allocation. Such sub-optimal allocation leads to considerable losses to society. Decisions on the use of competing energy systems or building technologies used for insulation are regularly based upon the relative costs at which the energy service desired, a room temperature of about 20°C, can be delivered. Companies or households making such decisions are considering the costs occurring to them. These costs reflected by the market prices of the energy and building technologies and the operation and maintenance costs are referred to as internal costs.

Since the first publication by Pigou (1912) the existence of costs which are not reflected in the market prices of goods has been acknowledged in principle by economists and has been discussed at the theoretical level. Due to a lack of empirical analyses and data on the real extent of these so-called social or external costs they have not been taken into account in practical economic politics and market prices so for.

Since late in the 1970's the exclusive reliance on internal cost considerations for choices concerning competing energy systems seems to have become increasingly questionable. Since the 70s' air pollution from combustion processes has caused serious damage to the forests of many European countries, as has been documented by official studies and annual statistics.

While more than 50% of all German trees show traces of damage, a considerable portion of them are virtually dying. These and other environmental damages do not show up in the price of the energy generated by combustion processes. Thus, the seemingly cheap source of energy may be relatively expensive for society. The environmental costs induced can be handed on to third parties not involved in the production or consumption of the energy as in the case of the forest owners or in the case of people suffering from respiratory diseases due to air pollution from combustion processes.

Authors like Solow (1982), Wicke (1986) or Barbir *et al.* (1990) have pointed out such discrepancies between the energy costs of a business (internal costs) and the total energy costs to society. This discrepancy which was first pointed out by Pigou (1912) has been named 'social costs' by Kapp (1950 and 1979), a pioneer in this field of analysis. In the following the term social cost is used for all costs of the production and consumption process, which are handed on to third parties or future generations and, thus, are not included in market prices. This follows Kapp's definition (Kapp 1950) and not the general neo-classical definition, where most of these costs would be termed external costs.

The climate catastrophe due to the use of CFGs but also due to the imbalance of the production and natural absorption of CO_2 is another example of possible social costs from the use of energy, which are handed on to future generations by today's energy consumers. Again, the costs of a possible climate change do not show up in the market prices of energy generated on the basis of fossil fuels.

The nuclear accident at Chernobyl has shown that electricity production based on nuclear fuels may induce vast social costs due to the release of radioactivity from nuclear accidents in power stations or other parts of the nuclear fuel cycle. Nobody will get any compensation due to the health damages caused by the Chernobyl accident outside the USSR. Although thousands of cancer incidents have to be expected, the people hit will have to bear the costs without getting any financial assistance. Again this is an indication of massive social costs of energy consumption not taken into account in the price of nuclear electricity.

Since the reports of the *Club of Rome* in the 70s we know that non renewable energy resources are rather limited as compared to the present and foreseeable future energy consumption of the world. Energy price developments of the last thirty years show in the case of crude oil, for example, that long term scarcity is not adequately reflected in present oil prices (see Schneider, 1980 p.835). If this is the case, such energy sources are only seemingly cheap today due to the fact that future generations will pay high opportunity costs for present use. Again we have a case of social costs not included in the market prices of energy.

From the examples given we can conclude that energy production based on fossil or nuclear fuels induces substantial social costs; whereas, it would appear that the use of technologies for the rational use of energy like in the building and operation of houses and energy production from renewable energy sources involves far fewer and lower social costs. If this is the case, then in terms of a macroeconomic optimum, there may be too little investment in technologies for the rational use of energy and the use of renewable energy sources, resulting in high costs to society. If such social cost elements are not taken into account in life cycle costing, we may get rather misleading results of the most elaborate accounting procedures. Particularly the question of relative social costs of electric power has been heavily discussed internationally since 1988 when a first comprehensive report on the subject (Hohmeyer 1988) had been published. In the following the author will summarize the results of this discussion and draw some first conclusions with regard to the question of the relative total costs of renewable energy sources.

1.2 The social costs of electricity generation

The question arises - how large is the difference between the social costs (and benefits) of different means to deliver the same energy service, in our example the difference between the social costs of or wind energy and those of conventional electricity generation? Is this difference large enough to affect the market introduction and diffusion of the new technology? Although it is difficult, if not impossible, to quantify and monetize certain social costs, particularly those in the area of health and environmental damage, the estimated minimum net social costs of conventional electricity are compared with those of wind energy. Even though full monetization can at best remain an estimate, awareness of the minimum net social costs (the lowest possible realistic figures) cannot but help to improve an allocation process which hardly ever takes into account social costs. The results given should be interpreted as a first systematic overview producing very crude figures which can nevertheless be used as a base for some initial, corrective economic policy measures.

The study upon which this paper is based has been conducted within the climatic, economic, and administrative framework of the Federal Republic of Germany. Although the quantitative and monetary results are not directly applicable to other countries, the general approach is valid for any market-oriented economy.

There are a number of different energy cost categories born by third parties which ought to be taken into account in the comparison of different energy technologies. The following list gives an impression of the range of effects to be considered:

☐ Impacts on human health:
  - short term impacts like injuries
  - long term impacts like cancer
  - intergenerational impacts due to genetic damage;

☐ Environmental damages on:
  - flora, including crops and forests
  - fauna, including cattle and fish
  - global climate
  - material;

☐ Long term costs of resource depletion
☐ Structural macroeconomic impacts like employment effects;

☐ Subsidies like:
  - R & D subsidies
  - investment subsidies
  - operation subsidies
  - subsidies in kind for:
    - ✧ infrastructure
    - ✧ evacuation services in case of accidents;

☐ Costs of an increased probability of wars due to:
  - securing energy resources (like the gulf war)
  - proliferation of nuclear weapons know how through the spread of 'civil' nuclear technology;

☐ Costs of the radioactive contamination of production equipment and dwellings after major nuclear accidents; and

☐ Psycho-social costs of:
  - serious illness and death
  - relocation of population due to construction or accidents.

This list of possible costs excluded from the normal pricing of energy is not exhaustive but it gives an impression of the range of costs which need to be considered before one may conclude that a certain energy technology is too expensive to be used.

Although it is relatively easy to enumerate a substantial number of social cost categories, which are obviously not taken into account today, it is rather difficult to quantify many of these effects and to put monetary values on them. Like in the case of global warming due to anthropogenic emissions of greenhouse gasses we can describe a number of probable effects in qualitative terms while we can only guess others. The latest computer runs allow us to come up with some first quantification of probable global temperature rises, but a sound analysis of the damages induced and the damage costs to be expected seems extremely difficult today. We can only guess possible orders of magnitude of such damages. In general we are in the situation of a navigator trying to estimate and compare the size of different icebergs ahead of him while he can only see the tips of these icebergs in the fog. *Figure 1* tries to give an impression of this situation.

So far most empirical studies of the problem have focused on a few problem areas, mostly on effects on human health and environmental damages like Ottinger *et al.* (1990) or Barbir *et al.* (1990). It should be pointed out however that there is a growing number of publications in the field addressing different facets of the problem at the theoretical as well as at the empirical level. Two collections of papers on the subject should be pointed out beside the publications already mentions: First the special issue of Contemporary Policy Issues (1990) on *'Social and Private Costs of Alternative Energy Technologies'*, containing about twenty papers on the subject, and second a report of a German-American workshop on the subject *'External Environmental Costs of Electric Power Production'* (Hohmeyer and Ottinger 1991) containing about thirty papers on the topic. In September a second international workshop on the subject was held in Racine, Wisconsin, USA. The proceedings of this workshop (to be published soon) will give the most up to date review of the research and political actions in the field of social costs. Right now a major German study financed by the German Minister of Economic Affairs and carried out by Prognos AG, Switzerland, is about to be published. This will cover a very broad spectrum of aspects of social costs of energy. In the U.S. a second major study is under way for New York State, while the U.S. Department of Energy is conducting a parallel study together with the *Commission of the European Communities* on a system for external cost accounting for all stages of the different fuel cycles.

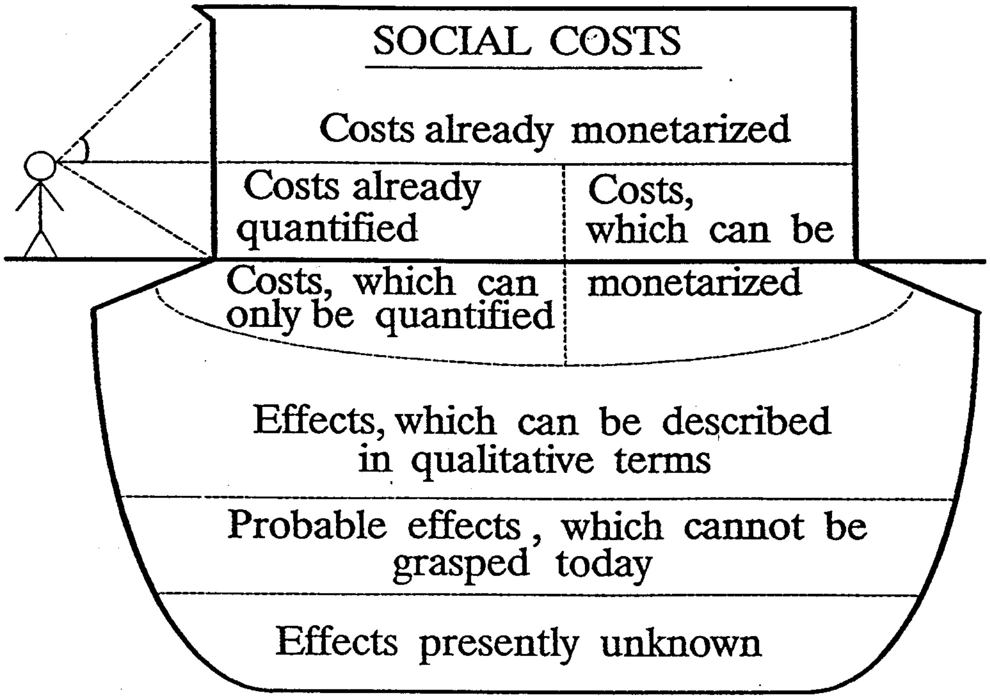


Figure 1: The situation of the present research on the full costs of different energy sources.

1.3 Empirical evidence on social costs used

The empirical evidence presented in the following is based on the author research on the subject (see Hohmeyer 1988,1989, 1990, 1991a, 1991b) taking into account much of the international discussion of the last three years. This work was centered around a comparison of conventional electricity generation based on fossil and nuclear fuels with wind energy applied in the Federal Republic of Germany. The areas of social costs covered are:

- ☐ Environmental effects;
- ☐ Impacts on human health;
- ☐ Depletion costs of non-renewable resources;
- ☐ Structural macroeconomic effects; and
- ☐ Subsidies.

Due to the scarce availability of empirical data and some fundamental problems in monetizing, a number of effects have not been quantified or specified in monetary terms by the author so far:

- ☐ Psycho-social costs of serious illness or deaths as well as the costs to the health care system;

☐ Environmental effects of the production of intermediate goods for investments in energy systems and the operation of these systems;
☐ Environmental effects of all stages of fuel chains or fuel cycles (specifically in the case of nuclear energy);
☐ Full costs of man made climate changes;
☐ Environmental and health costs of routine operation of nuclear power plants;
☐ Hidden subsidies for energy systems;
☐ Costs of an increased probability of wars due to:
  - securing energy resources (like the gulf war)
  - proliferation of nuclear weapons know how through the spread of 'civil' nuclear technology; and
☐ Costs of the radioactive contamination of production equipment and dwellings after major nuclear accidents.

Accordingly one should interpret the results presented in the following as a preliminary overview producing rather crude and low figures. Wherever doubt exists, assumptions have been made favoring conventional energy and counter to the underlying hypothesis - that the social costs of systems using renewable energy sources are considerably lower than those of systems using conventional energy. Thus, the author feels confident that the difference in the real social costs between the renewables considered and the conventional electricity generation in Germany is even larger than these results show.

1.4 Methodological remarks on the results derived

The environmental and health damages due to the use of fossil fuels have been quantified on the basis of numerous German studies on the matter. Most of the time, possible damage ranges for certain types of damages resulted. The aggregated damage costs have been attributed to electricity production according to its share of emissions of the most important air pollutants after weighing these pollutant emissions with their relative toxicity. Little information is available on the possible damages of CO_2-emissions through global climate changes. In general the social costs of environmental and health impacts have been measured as roughly attributable damage costs. In contrast to this approach other author favors control cost estimates as proxies for the actual damage costs, as these are easier to analyze, while some advocate contingent valuation procedures like 'willingness -to-pay' analyses, which allow to cover a broader range of impacts as direct costing. Because the control cost approach allows for a substantial level of arbitrariness due to the emission level allowed and because the contingent valuation methods result in somewhat less reliable results, these approaches have been chosen for the analysis only in rare cases. Control costs have been used for some first estimates on CO_2-emission impacts through global climate change. The figures used are based on an overview of U.S. studies on the subject published by Koomey (1990).

In the area of environmental and health damages from nuclear electricity, only the health damages of major nuclear accidents have been taken into account. These damage costs have been calculated on the basis of the reactor accident at Chernobyl and the latest German nuclear reactor safety study (GRS 1898). Taking into account the population density of the FRG, the probability of radiation induced cancer, the probability of such a nuclear accident and the losses in production potential due to cancer incidents caused, we have tried to monetize these costs. The value of a human life is set at 1 Mill. DM (about 0.5 Mill. $U.S.) according to the lost production potential. This, of course, is rather cynical and does not nearly reflect the real losses and human hardship involved. Based on industry figures for avoided deaths, Buchanan (1988) calculates 3-10 Mill. \$U.S. per human life, six to twenty times more than our calculations. Ottinger (1990) quotes different US studies on compensation payments and the willingness to accept additional risks giving a range of 1-12 Mill. \$U.S. per life lost. For his own calculations he uses a figure of 4 Mill. \$U.S. per life.

The depletion of non-renewable energy resources does not show up sufficiently in the energy prices. The present energy prices do not secure that future generations will have access to energy services at fair prices. Present price signals and the short-sighted economic utility theory discounting future needs at incredible rates lead to a waste of energy today at the expense of future generations. Many governments like the U.S. Federal Government prescribe the use of a 10% real depreciation rate for project evaluations. In contrast to present economic paradigms, justice in the distribution of energy resources over time is possible as soon as renewable energy sources are taken into consideration. If we consider the non-renewable energy resources of the world as an energy capital inherited by mankind and solar energy as our daily energy income which we may harvest by technologies utilizing renewable energy sources, a very simple idea can be applied to secure justice in the distribution of energy sources across all present and future generations achieving long term sustainability by very simple means.

Energy services can be supplied by drawing on our energy capital or on our energy income. Today the second is the more expensive way, while it does not diminish future availability of energy services as using part of the energy capital does. If we want to keep this availability constant when we are reducing our energy capital, we need to set aside funds for additional future investments in technologies utilizing renewable energy sources to keep the future availability of energy services constant by 'reinvestment'.

Based on the costs of a renewable backstop technology and the fact that the funds set aside will be needed when the non-renewable energy sources are depleted, we can calculate the present value of the necessary reinvestment surcharge as:

$$S(t_o) = S(t_n) \times (1 + i)^{-n}$$

S is the reinvestment surcharge and i is the real interest rate which can be earned by long term assets. The strategic life span (n) of the resource may be calculated by dividing all reasonably assured resources by the present annual consumption (depletion). To fully achieve intertemporal justice we have to consider equal energy services per capita. This demands the extrapolation of the present total energy consumption based on the future development of the world population. From the following function the strategic life span can be derived:

$$R(t_o) = \sum_{n=t_o}^{t_e} q(t_o) \times \frac{P(t_n)}{P(t_o)}$$

Where,
$R(t_o)$: Resource today
$q(t_o)$: Annual consumption today
$P(t_o)$: Population today
$P(t_n)$: Population of year *n*

On the basis of the life spans calculated and the reinvestment cost of the backstop technology assumed, the reinvestment surcharges have been calculated. These surcharges secure even access to energy services of all generations through their reinvestment in backstop technologies.

The macroeconomic impact on production, employment and growth has been analyzed with the help of an enlarged input-output table which has been supplemented by technology specific production functions of the energy technologies under analysis. To derive net effects, a direct comparison of the new and the substituted energy technologies is necessary. The direct and indirect subsidies for different energy technologies are given for the Frg. The largest subsidy per kWh are the R&D subsidies for nuclear power, while the R&D subsidies for fossil fuels are very small and the total R&D subsidies for wind are substantial.

1.5 Aggregated results and comparison of social costs

When the quantified social costs of conventional energy systems for the production of electricity based on fossil fuels are totaled and standardized for the production of 1kWh, gross social costs in the range of 0.03 to 0.16 DM_{82}/kWh result.. The value of 1 DM at the time of writing is about 0.6 $US or approximately 0.37 GBS. For electricity generated in nuclear reactors (not considering fast breeder reactors) gross social costs in the range of 0.1 to 0.7 DM_{82}/kWh result.. A weighted average for these gross social costs according to the fuel composition found in the Federal Republic of Germany's electricity generation in 1984 is 0.05 to 0.29 DM_{82}/kWh. The figures quoted reflect the recalculated results of the author taking into account the arguments of the national and international discussion since the first publication in 1988 (Hohmeyer 1988). *Table 1* summarizes the social costs of different means of electricity generation quantified in monetary terms. The first column of the table gives the results published in 1988 and the second column shows the results after recalculation in late 1990 for the case of older fossil power plants (emission level 1982) and new power plants (emission level 1990).

When one considers the social costs and benefits of electricity generated by wind energy - with the social costs of present electricity generation included as avoided costs - total social net benefits in the range of 0.05 to 0.28 DM_{82}/kWh result. This can be considered as a probable range for the minimum social net benefits of wind energy. All assumptions *underlining* these figures minimize the advantages of renewable energy sources. Therefore, in cases of doubt, the probable social benefits of wind energy are considerably greater than these figures show. This point has been proven through all national and international discussions on the first results published by the author in 1988 (Hohmeyer 1988).

Even without including all social costs and even with a deliberate bias against renewable energy sources, the net social benefits in monetary terms of wind energy are comparable with the basic market prices of conventionally generated electricity. Thus, any statement on the too high relative costs of renewables has to be reconsidered in the light of a full cost analysis taking into account the substantial differences in social costs between conventional electricity generation and renewables. The handling of the social costs may have a considerable effect on the time schedule for the market introduction and diffusion of seemingly expensive technologies utilizing renewable energy sources. Very similar considerations apply to many technologies for the ration use of energy.

Table 1: Comparison of the social costs of electricity generation based on fossil fuels, nuclear energy and wind energy published in 1988 and the results of recalculation performed in late 1990 (all figures in PPf/kWh, 1 Pf = 0.01 DM or 0.6 cents, 1982 prices).

		Hohmeyer 1988 (p. 8)	New calculations 1990	
			Fossil power plants 1982	New fossil power plants 1990
a)	Gross social costs of electricity generated from fossil fuels (all figures are estimated minimal social costs			
1.	Environmental effects	1.14-5.09	2.6-10.67	2.05-7.93
2.	Depletion surcharge (1985)	2.29	0.67-4.71	0.67-4.71
3.	Goods and services publicly supplied	0.07	0.06	0.06
4.	Monetary subsidies (including accelerated depreciation)	0.32	0.30	0.30
5.	Public R&D transfers	0.04	0.02	0.02
6.	Total	3.86-7.81	3.65-15.76	3.11-13.03
b)	Gross social costs of electricity generated in nuclear reactors, excluding breeder reactors (all figures are estimated minimal social costs)			
1.	Environmental effects (human health)	1.20-12.00	3.48-21.0	3.48-21.0
2.	Depletion surcharge (1985)	5.91-6.23	4.88-47.42	4.88-47.42
3.	Goods and services publicly supplied	0.11	0.11	0.11
4.	Monetary subsidies	0.14	0.14	0.14
5.	Public R&D transfers	2.35	1.46	1.46
6.	Total	9.71-20.83	10.06-70.00	10.06-70.00
c)	Average gross social costs of the electricity generated in the FRG in 1984			
1.	Costs due to electricity from fossil fuels (weighting factor 0.705[1])	2.87-6.56	2.58-11.25	2.19-9.19
2.	Costs due to electricity from nuclear energy (weighting factor 0.237[2])	2.48-5.32	2.38-16.62	2.38-16.62
	Total (conventional energy)	5.35-11.88	4.96-27.87	4.57-25.81
d)	Net social costs of wind energy			
1.	Environmental effects (noise)	(-0.01)	(-0.01)	(-0.01)
2.	Public R&D transfers (estimate)	(-0.26)-(-0.55)	(-0.16)-(-0.33)	(-0.16)-(-0.33)
3.	Economic net effects	0.53-0.94	0.47-0.78	0.47-0.78
4.	Avoided social cost of present electricity generation	5.35-11.88	4.96-27.87	4.57-25.81
	Total social benefits rounded to two digits	5.6-12.30	5.26-28.32	4.87-26.25
	Mean	8.90	16.80	15.60

[1] Old weighting factor 0.7444

[2] Old weighting factor 0.2556

1.6 The effect of social costs on the competitive situation and market diffusion

How can we analyze the impact of the consideration of social costs on the competitive position of a new versus an established technology? For this we look at a two-product market, as shown in *Figure 2*.

The costs of the established technology are gradually increasing, due to, for example, rising exploration and mining costs, while the costs of the new technology based on renewable energy sources or for the rational use of energy are decreasing considerably over time due to technological learning. Such developments can empirically be shown for conventional electricity and wind energy. At the point t_0 the new energy technology reaches cost-effectiveness if no social costs are considered. The substitution process can start at t_o.

Figure 3 shows the effect of including the net social costs. These are defined as the difference between the social costs of the conventional electricity generation and the new technology.

A static application of the social costs of a base year (e.g., 1985) results in a parallel projection of the market price curve of the conventional electricity. This results in a new intersection with the energy cost curve of the renewable energy source, showing that the new energy technology reaches cost-effectiveness at t_0 minus Δ_t equal t_1. If the social costs reach a sizable order of magnitude we get a distorted competitive situation, giving the wrong price signals for the choice of energy technologies. If we consider that cost-effectiveness does not lead to instant technology substitution, but that we find a substitution (or market diffusion) process which may stretch over 20 or more years, we can picture the impact of not considering social costs as a shift of the market penetration curve of the new technology by Δ_t.

If social costs are not considered, the whole diffusion process is delayed by this time span as compared to the best possible diffusion time schedule for society.

The social costs empirically quantified given in *Table 2* are applied in the following analysis of the future competitive position and market diffusion of wind energy. *Figure 5* shows the impact of including social costs on the competitive situation and on the resulting market diffusion of wind energy systems in the Federal Republic of Germany. All assumptions for this analysis are given in *Table 2*.

For the electricity costs of small wind energy systems of 50 to 100 kW nominal power, a cost curve has been derived on the few available German wind energy cost figures for the period 1980-12986 and on well documented Danish wind energy data for the year 1975-1985. As we see from figure 5(a) the German wind energy cost curve intersects with the market price curve of the electricity to be substituted at point A(2002). At this point in time wind energy produced by a private auto producer is competitive with the electricity from the grid which is to be substituted at market prices not including social costs.

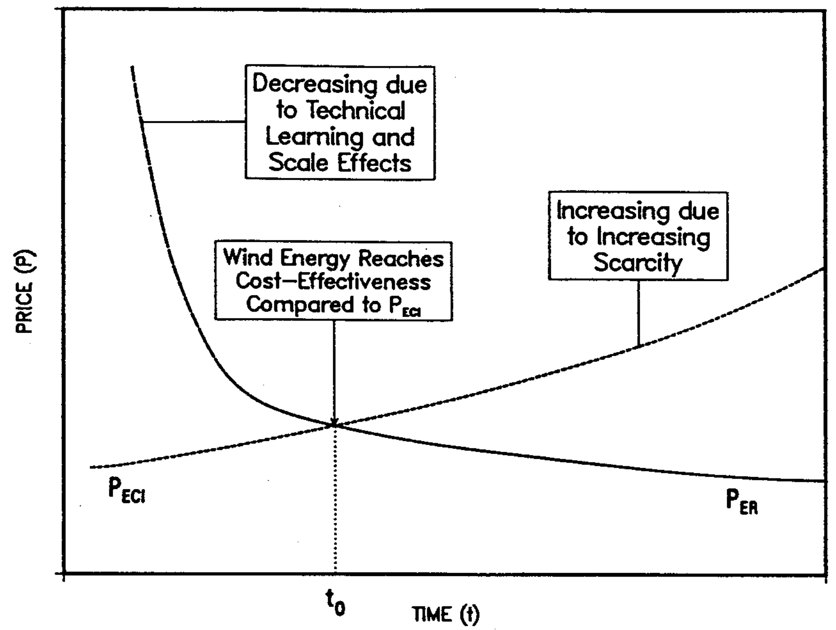


Figure 2: Cost development of electricity generation over time (no social costs considered) .
P_{ER}: Wind energy as an example for renewable energy sources
P_{ECI}: Conventional electricity, only internal costs

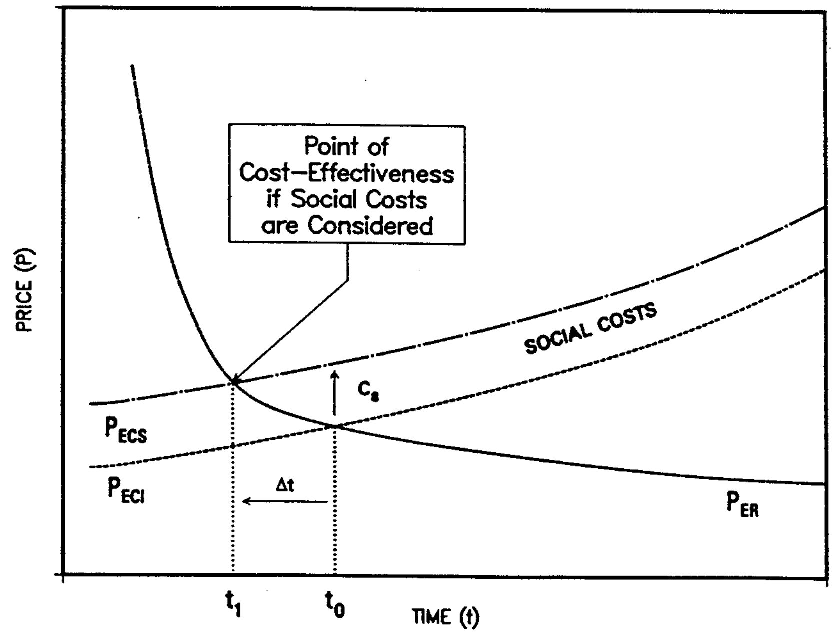


Figure 3: Cost development of electricity generation over time (social costs considered)
P_{ER}: Wind energy as an example for renewable energy sources
P_{ECI}: Conventional electricity, only internal costs

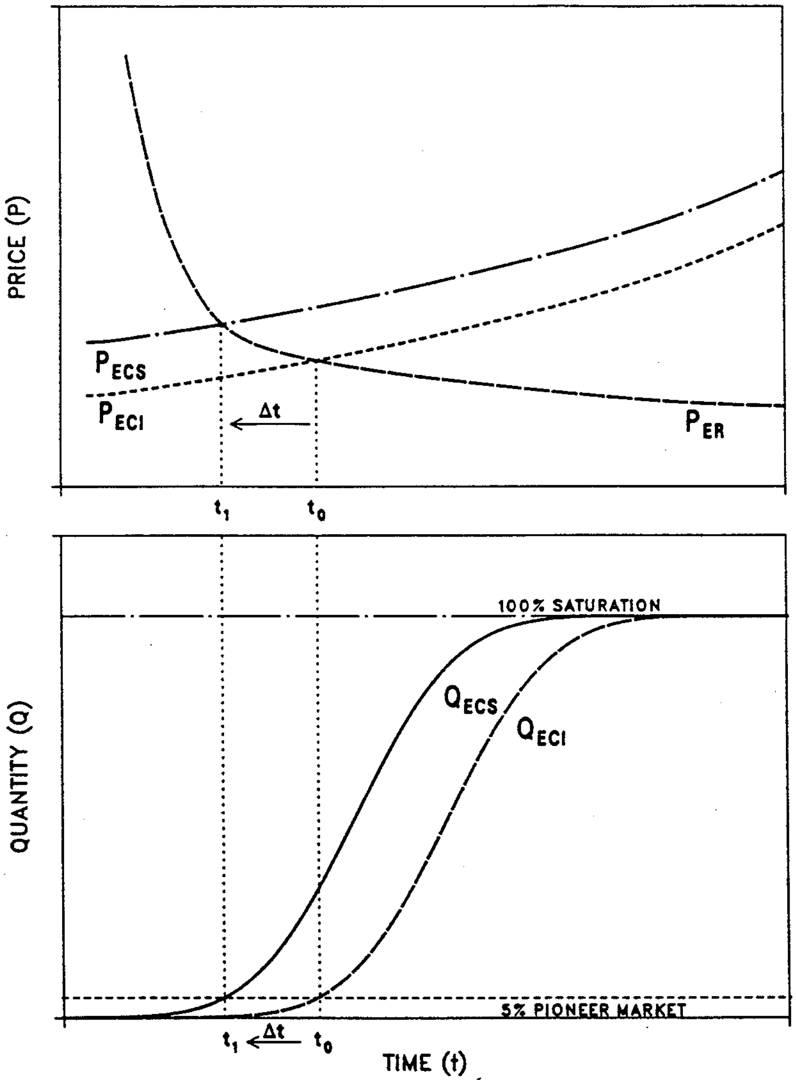


Figure 4: Market diffusion of wind energy due to the handling of social costs
QECI: Market diffusion curved without considering social costs
QECS: Market diffusion curve taking into account social costs

Table 2: Assumptions underlying the analysis of social costs and the impact of the competitive situation of wind energy (Hohmeyer 1989)

1.	General Assumptions		
	1.1	Price of Substitutable Conventional Electricity (1982)	25.1 Pf$_{82}$/kWh
	1.2	Working price (62.5%)	15.6 Pf$_{82}$/kWh
	1.3	Payment for Electricity Supplied to the Public Grid	6.5 Pf$_{82}$/kWh
	1.4	Real Price Escalation of Conventionally Produced Electricity	2%/Year
	1.5	Real Interest Rate for the Financing of New Investments in Wind and Photovoltaic Installations	5%/Year
	1.6	Market Potential for Wind and Photovoltaic Installations	20% TWh/Year
	1.7	"Pioneer Market" (5% of the market potential)	1TWh/Year
	1.8	Time Period for the Diffusion Phase (5% to 95%)	20 Years
2.	Assumptions About Wind Energy		
	2.1	Share of Wind Energy Consumed by Owner	20%
	2.2	Share Sold to Utility	80%
	2.3a	Compound Gain of Wind Electricity (1982)	10.2 Pf$_{82}$/kWh
	2.3b	Compound Gain of Wind Electricity Based on Working Price Assumption	8.3 Pf$_{82}$/kWh
	2.4	Life Expectancy of Wind Energy Facilities	15 Years
	2.5	Annuity	9.63%/Year
	2.6	Operating and Maintenance Cost	1.5%/Year
	2.7	Wind Energy Costs in West Germany[a]	
		1980	44.8 Pf$_{82}$/kWh
		1986	19.6 Pf$_{82}$/kWh
		1990	15.0 Pf$_{82}$/kWh
		2000	12.1 Pf$_{82}$/kWh
		2010	10.2 Pf$_{82}$/kWh
		2030	8.4 Pf$_{82}$/kWh
	2.8	Wind Energy Costs in Denmark[a]	
		1980	12.5 Pf$_{82}$/kWh
		1986	9.1 Pf$_{82}$/kWh
		1990	7.6 Pf$_{82}$/kWh
		2010	7.4 Pf$_{82}$/kWh
		2030	7.0 Pf$_{82}$/kWh

Pf$_{82}$ = Pfennig, 0.01 of a German Deutsche Mark, 1982 prices
TWh = Terawatt hour
DM = Deutsche Mark in 1982 prices

[a] For the electricity costs of small wind energy systems of 50 to 100 kW nominal power, a cost curve has been derived. These estimates are based on the few available German wind energy cost figures for the period 1980-1986 and on well-documented Danish wind energy data for the years 1975-1985.

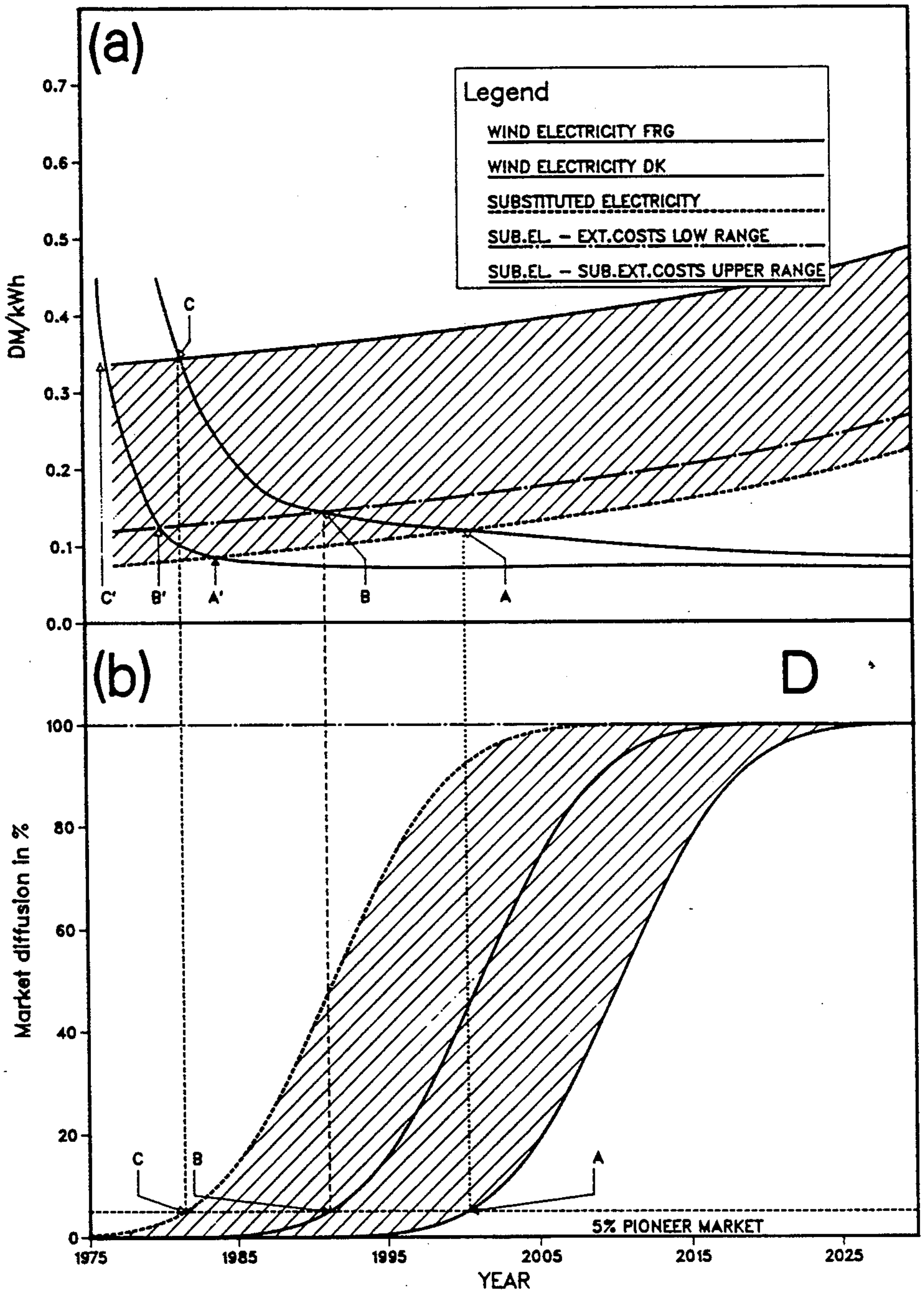


Figure 5: Influence of social costs on starting point of market penetration of decentralized wing energy systems and future market diffusion to year 2030.
(a) Costs for electricity from wind energy compared with costs for substituted conventional electricity.
(b) Market penetration of wind energy based on costs shown above

Adding the lower range of the estimated minimum net social costs (0.05 DM_{82}/kWh based on new fossil power plants) to this market price curve results in a second curve for the substituted electricity where point B(1991) is the new point of cost effectiveness for wind energy. Adding the upper range of the minimum net social costs of electricity (0.26 DM_{82}/kWh based on new fossil power plants) to the market price of substituted electricity gives a third intersection C(1981) as new point of cost effectiveness of wind energy. ***Figure 5(b)*** shows the resulting change in market penetration of wind energy systems resulting from this altered competitive situation. We can conclude that including social costs wind energy is competitive considerably earlier than market prices show. Accordingly, the market penetration of wind energy systems starts much earlier.

Although there are still major problems in the estimation of social or external costs, the approach seems to have some benefits for any attempt to arrive at total costs of different economic activities. It seems likely that life cycle costing in the building sector may benefit from the use of attempts to arrive at first estimates of the related social or external costs.

2.0 A new tool for hybrid analysis - an extended input-output model including physical emission and energy coefficients

2.1 Life-cycle analysis and intermediate production (horizontal and vertical impact chains)

Normal life-cycle analysis is based on the technical analysis of a vertical process chain from the mining of a raw material, through the production to the deposition of the final product. To consider more than the direct environmental impacts of the main links of this production, use and deposition chain 'horizontal chains' have to be considered as well: Each production activity requires production inputs in the form of intermediate products, which are produced utilizing other intermediate products themselves. The analyst is caught in a situation where he would need to keep track of an infinite number of intermediate levels of production and the corresponding emission from all processes involved. In practice life-cycle analysis terminates the follow up of such side branches relatively soon. Experiences with the IDEA model show that even the analysis of a few side branches requires a very substantial computational effort. A possible way to overcome these difficulties and to analyze all intermediate production and emission effects is the use of input-output analysis. If the basic economic instrument of input-output tables is augmented by branch specific emission coefficients a comprehensive analysis of all intermediate emission effects of a given production is possible. Thus, such an instrument is an ideal extension of the basic life-cycle analysis. In a sense it allows us to look at the effects running horizontally through the economy while life-cycle analysis concentrates on the vertical process chain. Thus the use of input-output analysis makes it possible to take all emissions into account caused by the production of a specific product.

2.2 Total cost calculation and intermediate emissions of production and consumption

Total cost calculation attempting to include external environmental costs as well as internal costs of production and consumption have to address the question of intermediate emissions and related environmental costs as well as the effects due to direct emissions. The former aspect is of special importance for technologies having comparatively little impacts through their direct use, like heat insulation, but large impacts through the production of intermediate goods necessary for their own production. While it may be possible to capture first order intermediate effects through life-cycle analysis for relatively simple technologies (e.g., heat insulation), the analysis of second order intermediate effects and first order effects for complex technologies (e.g., nuclear power plants) is rather complex if not impossible. Thus, a true analysis of 'total costs' requires an instrument allowing to capture intermediate emissions comprehensively as a basis for the analysis of intermediate environmental costs. Again such a tool is the augmented input-output analysis including branch specific emission coefficients.

If life-cycle costing attempts to capture the total costs of different economic activities, the inclusion of intermediate emission effects is of particular relevance. Life-cycle costing can be used to compare different building technologies to various energy technologies. As these technologies can differ substantially with respect of their specific intermediate emissions, neglecting these effects may introduce a substantial bias into the analysis.

2.3 The input-output model

The Fraunhofer-Institute for Systems and Innovation Research (hg-ISI in the following) has developed such an augmented input-output model for the Federal Republic of Germany. Based on the official German input-output tables and a large techno-economic database containing specific emission coefficients this model allows the analysis of intermediate emissions of about 15 relevant air and waste water pollutants as well as 65 different types of waste. The basic advantage of using an input-output model is the identification not only of the direct but also of the indirect emissions of the production of a specific good.

Figure 6 show the basic design of such an enlarged input-output-system. The basic input-output model is a functionally aggregated open Leontief-Model consisting of 58 branches. The economic tables used, which are supplied annually by the German Federal Statistical Office, serve as a basis for the German input-output tables supplied to the EEC as part of the European input-output tables. Beside the economic input-output tables the Federal Statistical Office publishes corresponding annual branch specific energy tables (in physical and monetary quantities) as well. To connect the input-output table of such a model, representing the production and consumption sector of the economy and its foreign trade relation, to the environment, branch specific emission coefficients have to be derived for each industry as well as the private sector of final demand.

2.4 The database

Basic input-output tables without emission coefficients plus additional economic data required (e.g., production statistics) are available from the *Federal Statistical Office of the FRG* as part of the official economic statistical system in the FRG. As the general input-output models and tables are well established the central challenge for the development of an integrated economic-ecological model is the determination of the specific emission coefficients for each industry. Therefore the main portion of the research effort to establish such augmented input-out model with branch specific emission coefficients is necessary to build up a database including most of the available statistical data on emissions from different sources as well s process specific emission data for important single production processes based on engineering analysis.

The calculation of such emission coefficients can draw on two different types of information sources. First, there may be some emission statistics disaggregated at the industry level, at the level of product groups or even at the production plant level which may supply data to be used for the calculation of specific emission coefficients. Secondly, there may be numerous technical information sources on process specific emissions, which can be drawn upon to derive very specific emission coefficients, which in turn can be aggregated to industry or sectoral emission coefficients. Aggregation to such level will generally draw upon disaggregated production (or energy) statistics to weigh the coefficients of each process or product group to derive the combined emission coefficients according to the production activities of the base year. *Figure 7* gives a schematic representation of the data base and calculation used to derive the emission coefficients to be included in the input-output tables.

Right now the database contains information on the traditional air pollutants plus CO_2 and some heavy metals, as well as on solid waste and waste water for all 58 branches. The data on solid waste and waste water has been derived from the official environmental statistics of the FRG. As the nomenclature of these statistics is different from the nomenclature of the input-output tables the German Federal Statistical Office had to rearrange this data to meet the specific needs of the model.

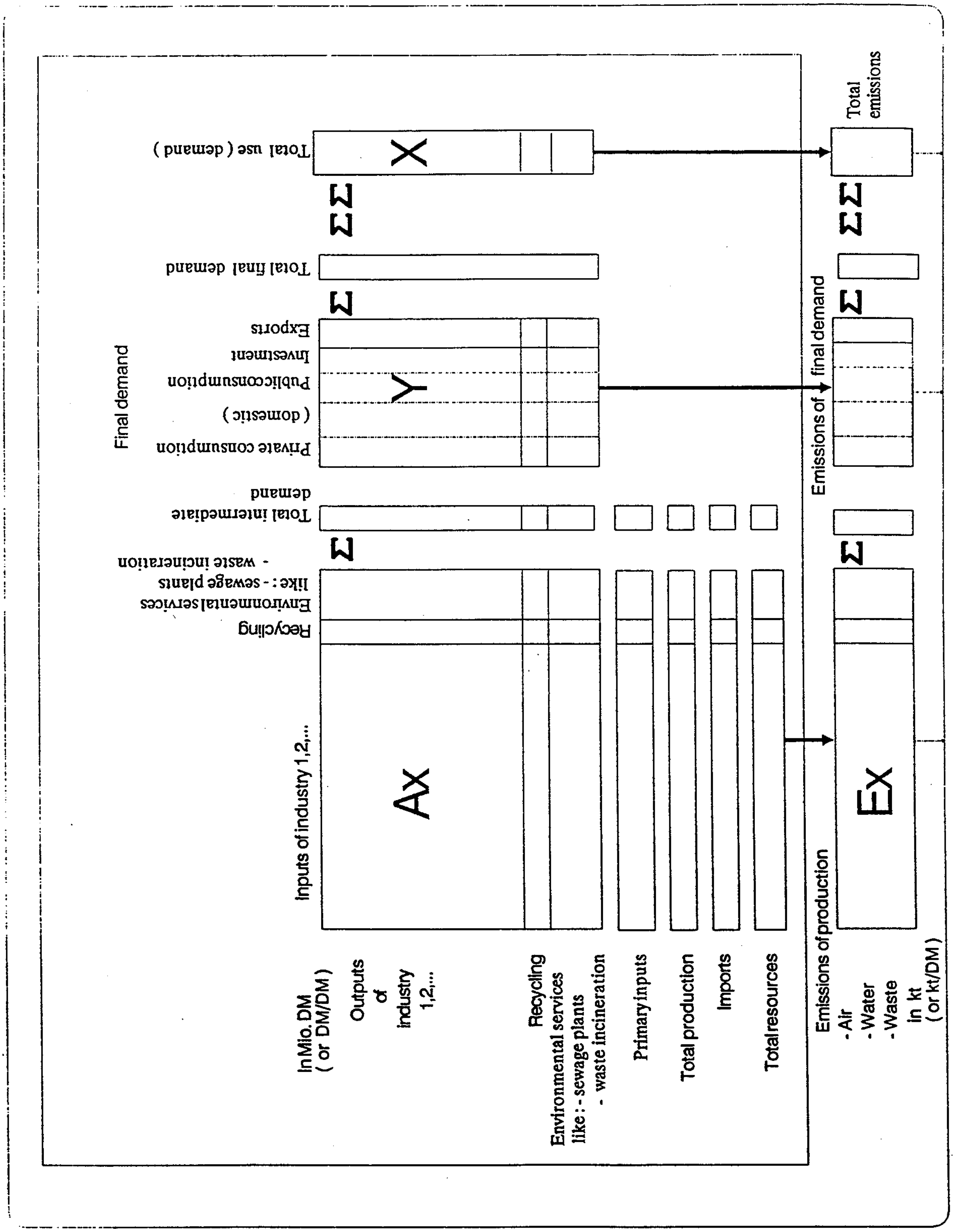


Figure 6: Enlarged input-output-table including specific emission coefficients for each industry and for the private sector of final demand

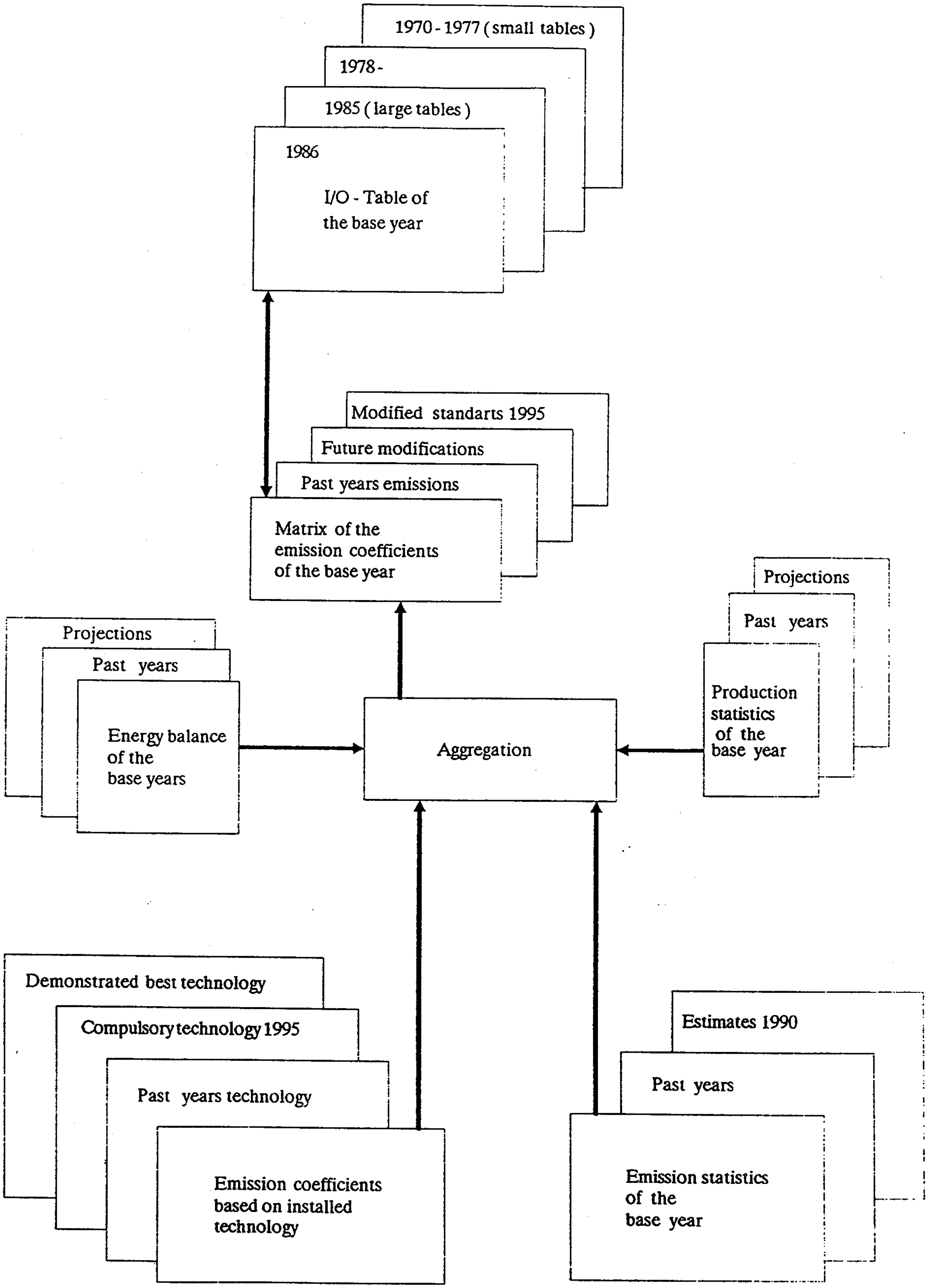


Figure 7: Data base for the calculation of specific emission coefficients to be included in the input-output analysis framework.

The data on traditional air pollutants plus CO_2 as well as the data on heavy metals is based on previous work of the Federal German Environmental Protection Agency and the FhG-ISI. Furthermore, specific engineering based information is included for three areas, which are aluminum production, iron and steel production and the production of NaOH (caustic soda) and Cl (chlorine) as base chemicals. For these areas a number of process-specific studies plus additional research within FhG-ISI was used to derive the data to be included in the model.

Beside the matrix of direct emission coefficients, a matrix of coefficients for all direct and intermediate emissions can be derived based on the Leontief-Inverse of the input-output-matrix and the direct emission coefficient matrix. Thus, direct and indirect emissions induced by production and final consumption can be analyzed in the framework of input-output analysis.

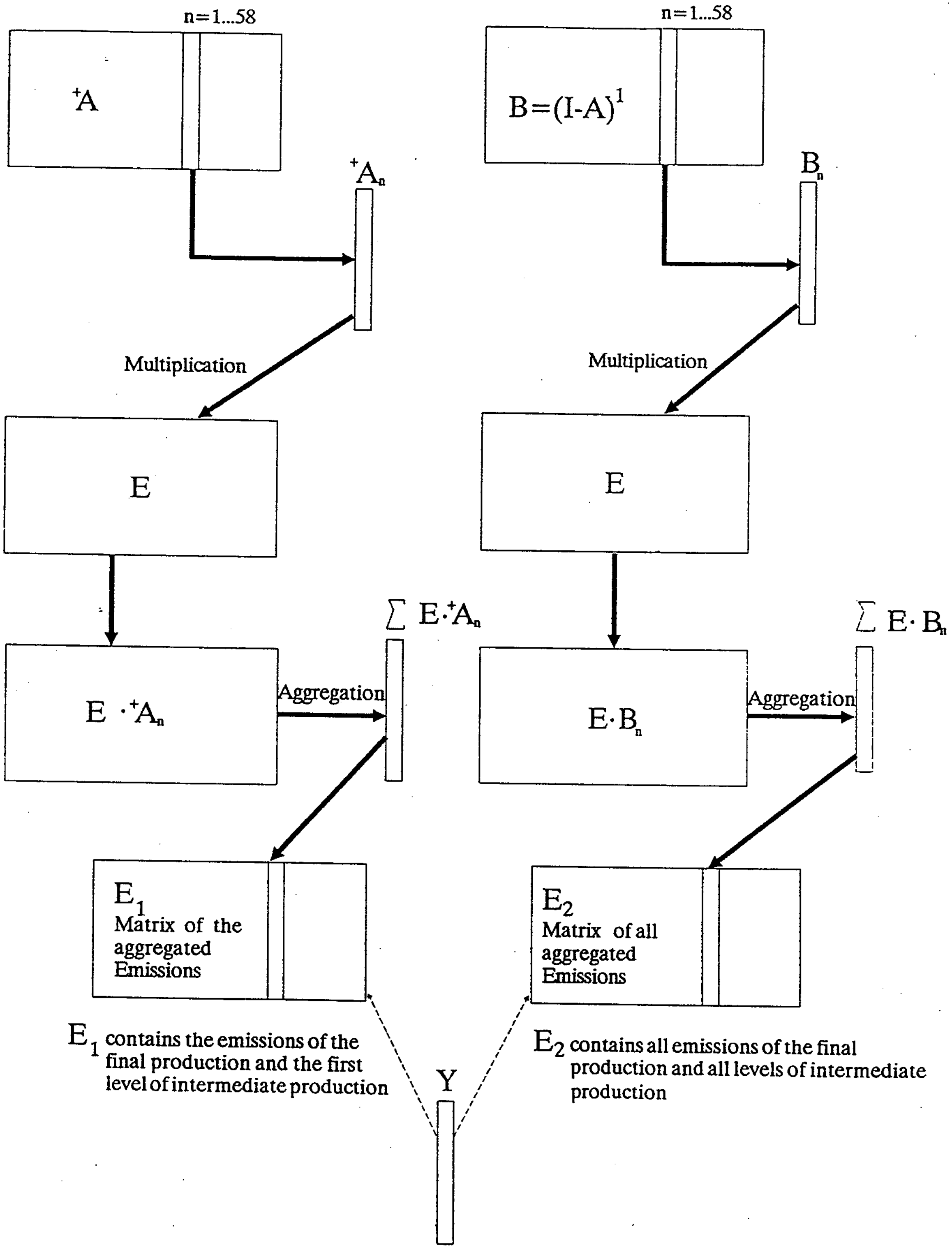
Furthermore different levels of intermediate production can be distinguished. *Figure 8* gives a schematic representation of the calculation of the different emission coefficient matrices for intermediate emissions of production. For each pollutant two kinds of indirect emission coefficients are calculated: Matrix E1 containing the emissions of the final production and the first level of intermediate production and matrix E2 containing all emissions of the final production and all levels of intermediate production.

Due to the various emission coefficients there exists more than only one interface of the model with traditional life-cycle analysis. Depending on the level of disaggregation of a traditional life-cycle analysis it is possible to calculate either all emissions of intermediate production or the intermediate production excluding the first level of intermediate production if this production level is included in the traditional life-cycle analysis. Thus, the augmented input-output model is a flexible instrument, which can be tailored to different levels of analysis.

In addition the user interface of the model allows to specify a variety of different scenarios to be analyzed. The model has an interactive link to the database allowing the retrieval of all relevant basic information on emission factors after the scenario for the analysis has been defined by the user. Thus, it is possible to specify the emission coefficients as well as the economic parameters for each single model run. The database is organized as a relational data bank using INGRES as the data bank software. The interface between the model and the database is programmed in SQL, while the model uses C and FORTRAN as programming languages.

2.5 State of the research today

The actual work on the development of the model, the database and documentation has just been completed and the model is used for first analytical tasks. *Figure 9* shows first results of the impact of intermediate production on the overall emissions caused by the production of various classes of products. The magnitude of the indirect emissions due to intermediate production clearly outweigh the direct emissions of all intermediate production into life-cycle analysis.



E_1 contains the emissions of the final production and the first level of intermediate production

E_2 contains all emissions of the final production and all levels of intermediate production

Multiplying the emissions coefficients (E_1 oder E_2) with a given final demand Y directly produces results for the emissions caused on all levels of production

Figure 8: Schematic representation of the calculation of intermediate emission coefficient matrices

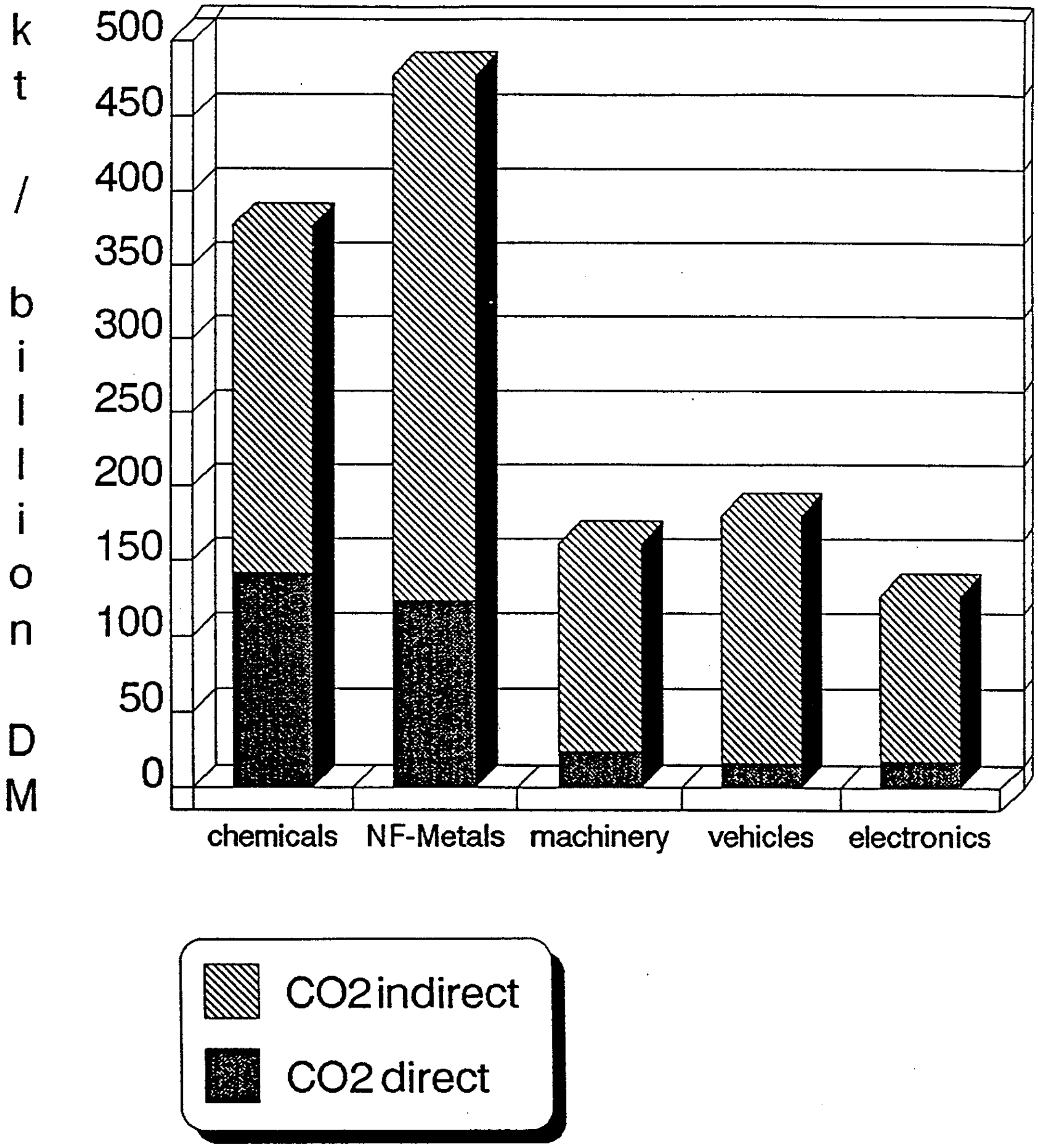


Figure 9: CO_2-emissions of direct production and indirect CO_2-emissions of intermediate production for various classes of products.

2.6 First results on technologies for the rational use of energy - the case of heat insulation

Figure 10 presents the results of a traditional life-cycle analysis comparing a low and a high insulation case of a single family home both heated with a natural gas heating system (Hoffmann 1991). Thus, it was possible to concentrate the calculation of the emissions of the natural gas heating system on the difference of the emissions of the two cases. This emissions difference for the heating system is shown in *Figure 10.* These additional emissions of the low insulation case are compared with the emissions due to the production of additional insulation materials necessary for the high insulation case.

The emissions for the natural gas heating system cover the vertical process chain of natural gas production, transmission, distribution and usage. The life-cycle analysis of the heat insulation includes the main vertical process chain of the production of the insulation material, e.g., the process chain for the production of polystyrol within the chemical industry.

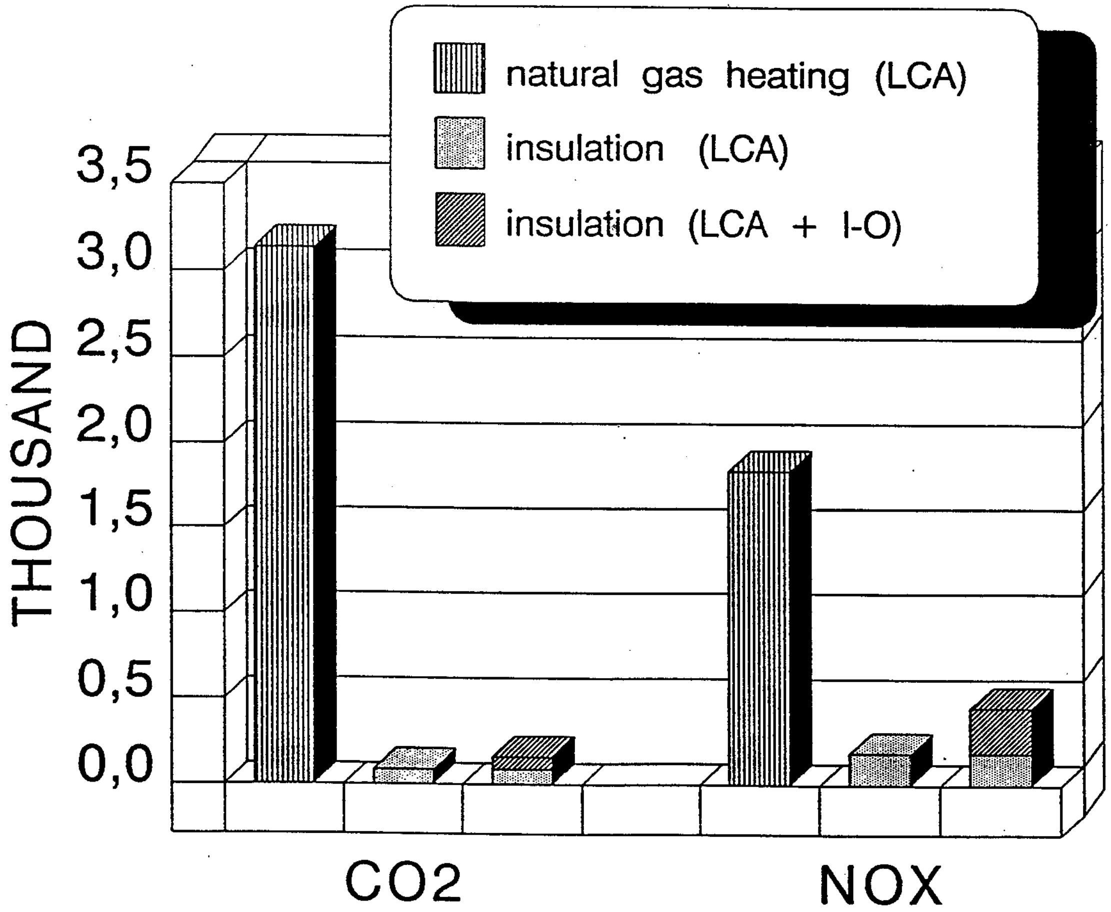


Figure 10: Annual CO_2 and NOx emissions of heat insulation of a single family house in comparison to a natural gas heating system.

As the life-cycle analysis of the heat insulation material terminates numerous side-branches running horizontally through the economy the augmented input-output model was used to calculate the emissions of intermediate production not included in the life-cycle analysis. *Figure 10* shows first preliminary results of the total CO_2 and NO_x emissions of all intermediate production necessary for insulating a single family home subdivided by emissions calculated by the life-cycle analysis and emissions calculated with the augmented input-output model. The order of magnitude of the latter (larger additional effects than those calculated by life-cycle analysis alone) demonstrate the need to include all levels of intermediate production into life-cycle analysis.

2.7 Possible contribution to life-cycle analysis and total costing approaches

The case of life-cycle analysis for heat insulation demonstrates that the use of an augmented input-output model can yield additional information on emissions otherwise neglected. Thus, the model can probably improve the data base for total costing approaches of different energy systems based on life-cycle analysis substantially.

The amount of emissions covered by the input-output model linked to a traditional life-cycle analysis depends on the complexity of the life-cycle analysis: A very detailed and complex - and therefore expensive - life-cycle analysis might be able to cover the most substantial part of the emissions. But even in this case the use o the input-output model can serve as a tool for plausibility checks estimating the portion of the emissions not included. Thus the input-output model can also be used as an instrument to determine when to terminate analysis with life-cycle analysis. However, very detailed life-cycle analysis will rather remain the exception than the rule due to the high specific costs.

Furthermore, the augmented input-output model covers not only the emissions of air pollutants but also waste water and waste. As life-cycle analysis of energy systems usually concentrates on air pollutants the use of the input-output model can yield data on additional pollutants otherwise neglected. With the increasing use of end-of-pipe technologies and the possible pollution transfer form one environmental media into the other information on waste and waste water becomes more and more important. This is demonstrated for example by the use of scrubbers decreasing the emissions of air pollutants but increasing the amount of highly toxic wastes. Such effects can be caught by the input-output model. Again the use of the input-output model can improve the information base for total costing approaches of different energy systems which have to take into account the environmental effects of increased amounts of waste as well.

Finally the use of an input-output model makes it possible to calculate the economic effects of different energy systems. Life-cycle analysis and total costing have to take these effects into account as well. Thus, the case for using an input-output model in addition to process-analysis based life-cycle analysis is supported furthermore.

As demonstrated the augmented input-output analysis can improve the data base of life-cycle analysis event though the input-output model works with aggregate data less accurate than process specific data. A combination of both methods for hybrid analysis seems to be the best way to perform life-cycle analysis, with the input-output model dealing with the effects otherwise neglected.

2.8 Combination of social cost estimates and the results of hybrid analysis

Once the analysis of social or external costs of the emission of certain pollutants arrives at specific cost figures per unit of pollutant emitted, like DM/t of CO_2, such costing figures can be applied to the physical results of hybrid analysis of all direct and intermediate emissions induced by the economic activities analyzed. If as a first approximation a linear emission to damage function is assumed, simple multiplication of the two results (quantities emitted times damages per unit) gives us a first order estimate for the direct and intermediate social or external costs to be included in our life-cycle cost accounting. If the social costs reach a substantial order of magnitude and if they differ substantially for alternative ways to deliver the same utility (e.g., energy service) their inclusion seems to be mandatory.

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The Integration of Environmental Impact Assessment Methods in the Planning Process of Buildings

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1. Introduction

The objective of the environmental optimization of a building during its lifecycle cannot for the present be met because of a lack of specific knowledge as well as appropriate planning and decision structures. The generally admitted need for a comprehensive approach implies that the interest of the concerned professionals converge, which is not necessarily so. They generally have different points of view and different objectives, even within the common objective of ecologically sound planning.

A first group is mainly interested in energy related problems. Knowing the consumption of operation energy, the (grey) energy embodied in materials, processes and the preparation of final energy itself, has been estimated with different methods. This approach has been enlarged by the extension to pollutants through emission coefficients of typical energy transformations and transport processes. The representatives of this group generally assume that the total primary energy consumption is a possible (and already existing) indicator for the environmental impact. The main objective lies in a rational utilization of natural resources and in an enhanced economical approach (through external costs).

A second group is mainly interested in human toxicological problems. The German *"Baubiologie"* is one of the tendencies, the international research community around Indoor Air Quality and Sick Building Syndrome another. The main objective is the creation of a healthy indoor climate, a largely anthropocentric point of view.

A third group is mainly interested in the (in our case destructive) consequences of human activities on the environment. Its objective is to (re)create natural cycles and to integrate the building process into these cycles. The range of preoccupation extends from simple recycling problems of building materials to the global Gaia approach [LOV].

These different approaches will probably continue for some time; there is no general unified theory in view [DEL]. All the approaches have produced methodologies and decision tools which have been applied or could be applied to the building processes with the aim of optimizing a building during its lifetime. Most approaches and tools share the following assumptions:

☐ The building has to be considered as a whole
☐ The building has to be considered during its lifetime
☐ The energy and material flows have to be known

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2.0The current situation in planning

Architects, engineers and other construction professionals have been exposed in recent years to a number of often contradictory demands:

Buildings should be airtight to save energy (to avoid the greenhouse effect), but airtight buildings might lead to high concentrations of toxic substances which in turn could be dangerous for the users (who have been saved from the greenhouse effect). The situation of the construction material market becomes more confused each year by the disappearance of traditional materials, the interdiction of new materials, the generalization of composites, etc. In this context, the great number of different assessment tools provokes a supplementary rise in confusion. [KOH92].

All the proposed tools establish a more or less explicit relation between causes and effects. The levels differ however: in the human-toxicological approach the choice of a building material is related to its effect on the user (e.g., allergies); in the eco-toxicological approach the production of building elements from the tropical forest, for example, is related to climatic changes.

There are three categories of tools which will be analyzed and compared in more detail:

a) Restrictions
In the form of the choices of production processes with an implicit evaluation.

2) Product declarations
The establishment of the inventory of a product or process within the chosen system limits. There is no evaluation other than the choice of the system limit and the choice of the indicated component.

c) Impact assessments
On the basis of an inventory, causes and effects are identified and evaluated. The evaluation models can differ very much in width and depth.

3.0 Restrictions

3.1 Laws, prescriptions

Politically determined prohibitions, limits or goals in the use of materials or classes of materials.

Form:	Rules, values, decision tables
Advantages:	The protection of humans or animals (their life and well-being) is regulated in a categorical way.
Disadvantages:	The establishment and the introduction often take a long time. There is a risk of side effects. The limit-values become objectives through the economical cost minimization. There are no incentives to go below the limit values.
Examples:	Interdiction of asbestos, classes of toxicology

3.2 Labels

Certain materials or products are analyzed in a standardized way and can obtain a label. The evaluation model is generally known, but implicit for the user. Labels constitute a positive list. [BUS91].

Form: Label

Advantage: Easy to use, facilitates the choice between known products. No problems with the producing industry.

Disadvantages: No transparency for the user. The evaluation model generally favors one type of impact (e.g., air pollution). It is rather difficult to change the labels.

Examples: "Blue Angel" in Germany, "Environmental choice" in Canada. A common European eco-label is planned.

3.3 Negative lists

Certain materials with a leading function (their negative effects on humans or on the environment are considered established) are identified and their use is discouraged.

Form: Lists.

Advantage: Easy to use, not very difficult to establish.

Disadvantage: They give only a limited security to the user. The conflicts with the industry are programmed and inevitable.

Examples: Several publications [SCH]

4.0 Product declaration

4.1 Product labeling

This tool is extensively used for medicaments, food and other consumer goods. The content of the product in its last production stage is indicated. The only evaluation is the choice of components.

Form: Standardized declaration of the components of a product.

Advantages: Creates a certain transparency for the user. As a specialized tool it stresses the importance of relevant components. The system works well in the medical and food sector for people with allergies. It could certainly be generalized for building materials in relation to allergy risks.

Disadvantages: There is no explicit relation between causes and effects; the user is rather helpless in the interpretation. The fact that the processes preceding the final state of the product are not taken into account can lead to wrong decisions concerning the eco-toxicology of a product.

Examples: Standardized product labeling for building products [SIA]

4.2 Life cycle analysis

The whole production-use-disposal process of a product is analyzed. The flows are attributed to products. The input-output equality (balance) assures that nothing gets lost. A product is charged with:

☐ The materials physically present in the product

☐ The materials physically produced during the whole process (including emissions, waste, byproducts etc.)

The total primary energy content is a very rough environmental impact indicator. There are several names in use: eco-balance, material and energy flow balance, life cycle inventory. [KOH86 and 91a].

Form:	Quantitative balances, Inventories
Advantages:	The only method to allow - through clear distinction of flows - a controlled application in the planning process.
Disadvantages:	Complicated to establish. No international agreement on how to situate the system limits. Without evaluation there is no immediate application in the planning process.
Examples:	Methods for life cycle inventory and life cycle analysis [BEW]

5.0 Environmental impact assessment

5.1 Life cycle impact assessment

To date, the incorporation of environmental quality aspects into management decisions faces two issues. Firstly, very little factual, quantitative information about environmental quality is available in a systematic way. Secondly, within the uncertainty which then arises, environmental discussions often become emotional and disregard important aspects while specific issues are highlighted. "Chemical of the month" initiatives and fast upcoming environmental waves, issues and fashions prevent long-term planning of sustainable solutions. LCA has the potential to handle these issues and to achieve authority in environmental quality assessment." ([SETAC, p3]).

There are different names in use: eco-profiles, environmental profiles.

Form:	Quantitative aggregated balances
Advantages:	Certain standardized methods allow judgment of the impact of a building on different parts of the environment, giving a certain transparency.
Disadvantages:	Few methods are sufficiently documented: Some are very specific (e.g., for the food industry). The results of the evaluation of the different methods are often fundamentally different. The condition of success of the system is a large library of reliable and up-to-date processes and materials, which does not exist yet.
Examples:	Life cycle impact assessment method for packaging materials [BUS] [BRA] [BfK]

The product line analysis (Produktlinienanalyse) developed in [GRIE] is an extension of the life cycle impact assessment to economic and social aspects.

5.2 Impact assessment

The environmental impact assessment methods are rather rigidly standardized methods to analyze the impact of a process in a specific situation. The method has mainly been used to estimate the impact of adequate energy transformation technologies and large power plants on a particular site. Similar techniques are used in transport and road construction.

Form: Different forms from checklists to detailed reporting formats.

Advantages: Correctly used, the method gives the best indications concerning the effects (impacts) on the environment of a building or a plant.

Disadvantages: The method does not generally consider the use of resources and other upstream processes (the life cycle aspect).

Example: In the field of the buildings, the British environment assessment for new office design methods [BRE].

5.3 Prototypes

This method derives from the "case based" reasoning techniques developed in artificial intelligence [RIE]. Most problems have been found to be too complex for decomposition into single units and traditional optimization techniques have proven incapable of finding solutions. The case based reasoning technique tries to link the solution of a new problem to the well known solution of a similar problem.

Form: A data base with analyzed cases.

Advantages: Traditional techniques being of little use, this technique, which is a rationalization of the traditional planning by types, is very promising.

Disadvantage: Still in research.

5.4 External costs

On the bases of life cycle inventories and life cycle analyses, the external (social) costs produced by certain technologies (costs for sickness, destruction of buildings and nature etc.) can be estimated. These costs can be integrated in the price of energy or they can take other forms (eco-bonus etc.). The proceeds can be applied to encourage other, less harmful technologies or protective measures [HOH] [WIE].

Form: Price supplements, taxes, eco-bonus.

Advantage: The method is market compatible;. is gives large possibilities of political action to avoid or to favor certain technologies.

Disadvantage: The basic data to calculate external costs are so far not sufficiently complete to overcome political obstacles.

The different tools can be situated in relation to the three mentioned approaches (points of view).

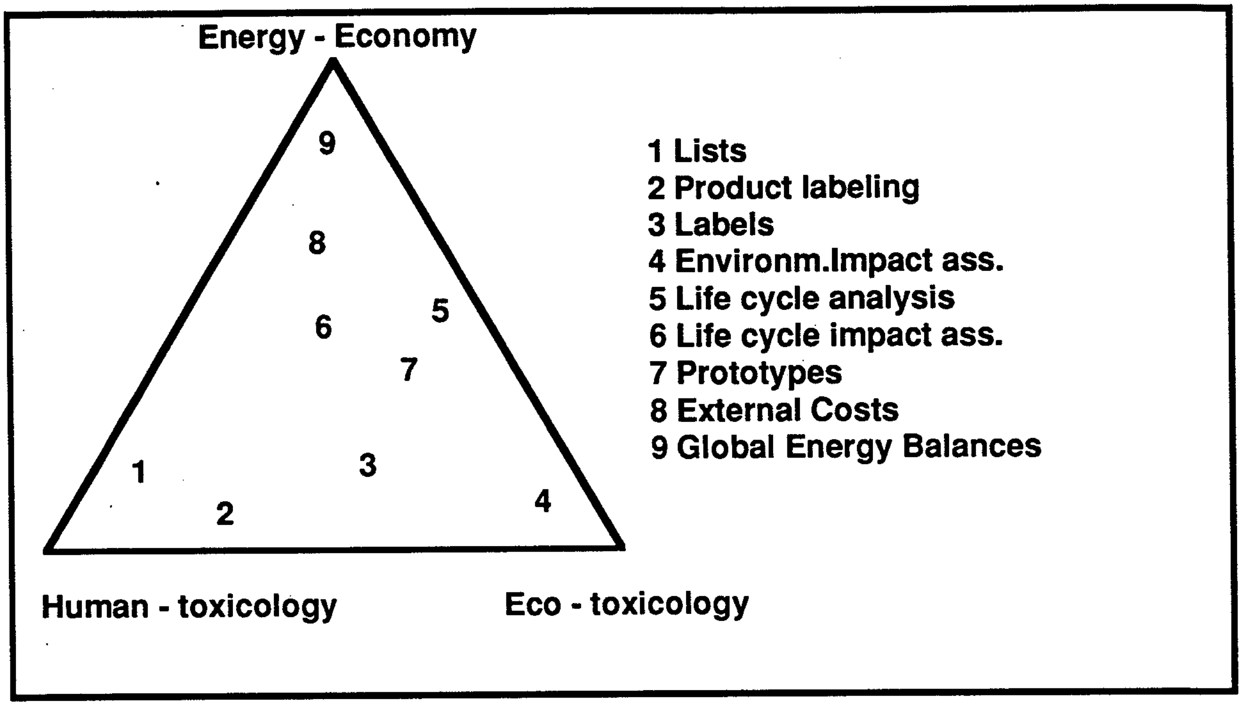


Figure 1: Tools and points of view.

6.0 Conclusions for the building process

The different evaluation methods and tools which were described and which are used today generally concern products with a rather short lifetime (e.g., packaging). Buildings have particular characteristics compared to usual consumer products:

- ☐ A much longer lifetime: 50-100 years
- ☐ A demand for operation during lifetime which is often much larger than the initial construction demand of materials and energy
- ☐ A specific need for energy and materials which is comparatively high
- ☐ A large quantity of different techniques used to produce objects for the same function
- ☐ An impossibility to predict the future use, refurbishment and disposal of the buildings.

These characteristics illustrate the need for new, original methods of evaluation and tools in the building sector.

Additional demands are:

- ☐ The methods must cover the complexity of actual and future building materials (composites)
- ☐ The methods must rely on rational analysis, be transparent and reproducible.
- ☐ The methods must permit integration of specific views and preferences of users.
- ☐ The methods must be adapted to the planning process.

None of the current tools respond to these demands. The professionals are obliged to use several tools and to choose the safest (least criticized) solution. Today there are three main approaches to this problem:

a) *The expert approach:*
The qualification of a new category of specialists who make decisions on the basis of their professional knowledge (whatever this means).

b) *The comprehensive planning approach:*
The development of procedural models in the planning process to integrate actual (and future) knowledge

c) *The building product model approach:*
The development of new, integrated, computer assisted planning tools (so-called intelligent CAD systems).

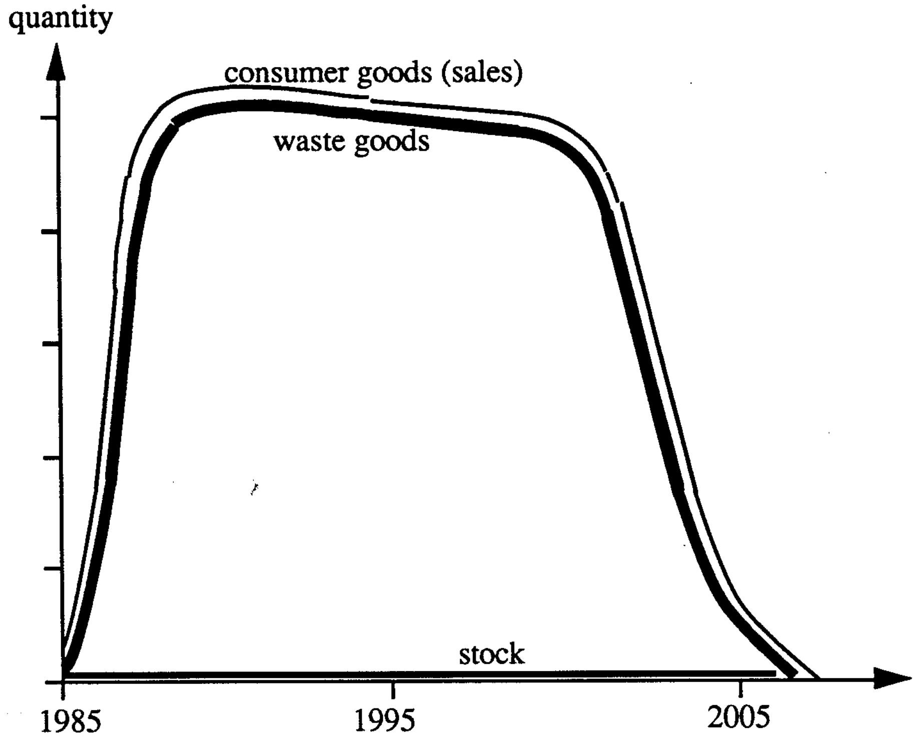
The author believes that further specialization inside the planning team is not an appropriate solution. The development of procedural planning models (comprehensive planning) is by now the only possible solution. This way of planning is relatively complex and can only be used for rather complicated and large buildings. The case of the common simple building and above all of its refurbishment is not taken into consideration at all. The development of intelligent CAD systems (based on building product models) is still in research.[INC]

7.0 Proposition for a procedural model

There is a need for planning tools which are adapted to the different phases of the planning process, making accessible to the architect at the earliest possible moment the necessary adapted information. We are looking for a genuine, generally applicable model which allows integration of quantitative and qualitative aspects. The model distinguishes 3 levels:

***Level 1:** Construction/transformation/refurbishment (principle decision)*
On this level, the request is analyzed to determine how it can best be satisfied (the need may be fulfilled by a building or by other means. It is an extension of the actual feasibility study. The objective is to compare the environmental impact of new construction, transformation or refurbishment processes. In the case of a demolition, the recycling has to be taken into account; in the case of a new construction, the additional sealing of natural surfaces has to be considered. In the case of transformation or refurbishment, the order and frequency of the different measures and their environmental impact has to be evaluated.

b **short residence time**
(days - week)



long residence time
(years)

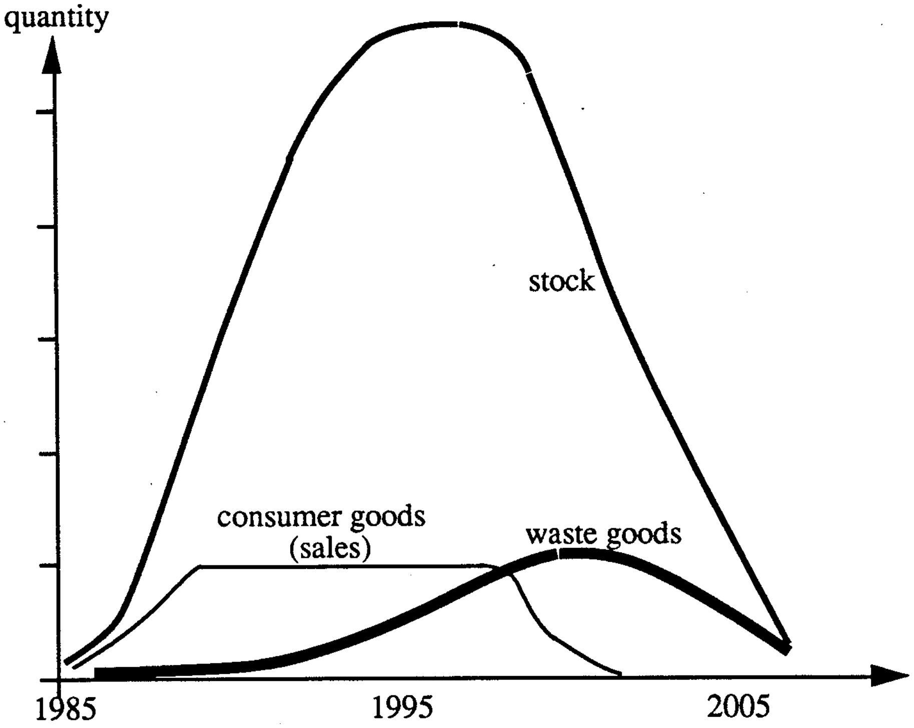


Figure 2: Residence time of consumer goods and building materials [BAC]

The general questions at this level are: yes/no - when

Phase:	before preliminary work
Responsible:	owner
Specialist:	architect or engineer

Instruments:
The evaluation can be based on the estimation of the specific primary energy consumption for operation and on the specific primary energy embodied in materials and the construction process. These data, related to the effective functional surface, can be transformed into energy transformation related emissions and aggregated in several ways. The emissions related to the process are neglected at this level. The tools would be indexes in the form of MJ/m^2 year of primary energy [KOH87].

Level 2: Building design
At this level, the decisions concerning the functional and constructive solutions as well as certain general material choices have to be made. From a very general point of view of energy and resource conscious building, the decision hierarchy could be the following:

1. Reduce the operation energy needs (u-value of walls and of glass; boiler efficiency, air-tightness etc.).
2. Reduce the material quantities in general (e.g., by reducing building mass to the thermally necessary quantity) and the quantities of energy intensive materials in particular.
3. Avoid materials and construction techniques implying the use of materials which harm the environment directly (CFCs in solvents etc.).

The final choice of building components and materials as well as of construction techniques will depend more and more not only on financial considerations, but also on environmental criteria. It is important to specify the type of evaluation which is going to be used to allow the production industry to improve or eventually replace their products. In the planning process, the most convenient way to situate these decisions is to add the energetical and environmental data to the financial data on building elements. By using the element classification for cost planning [CRB] these data can easily be integrated into the common general building cost planning software. Which energetical and ecological data will be specifically used is not yet clear. The ongoing research in Switzerland should produce a catalogue of elements within a year.

Phase:	scheme design / detail design
Responsible:	the planning team
Specialist:	different partners in the planning team

Instruments:
The ideal instrument would be a complete database with existing materials and components and the necessary energy and environmental data.

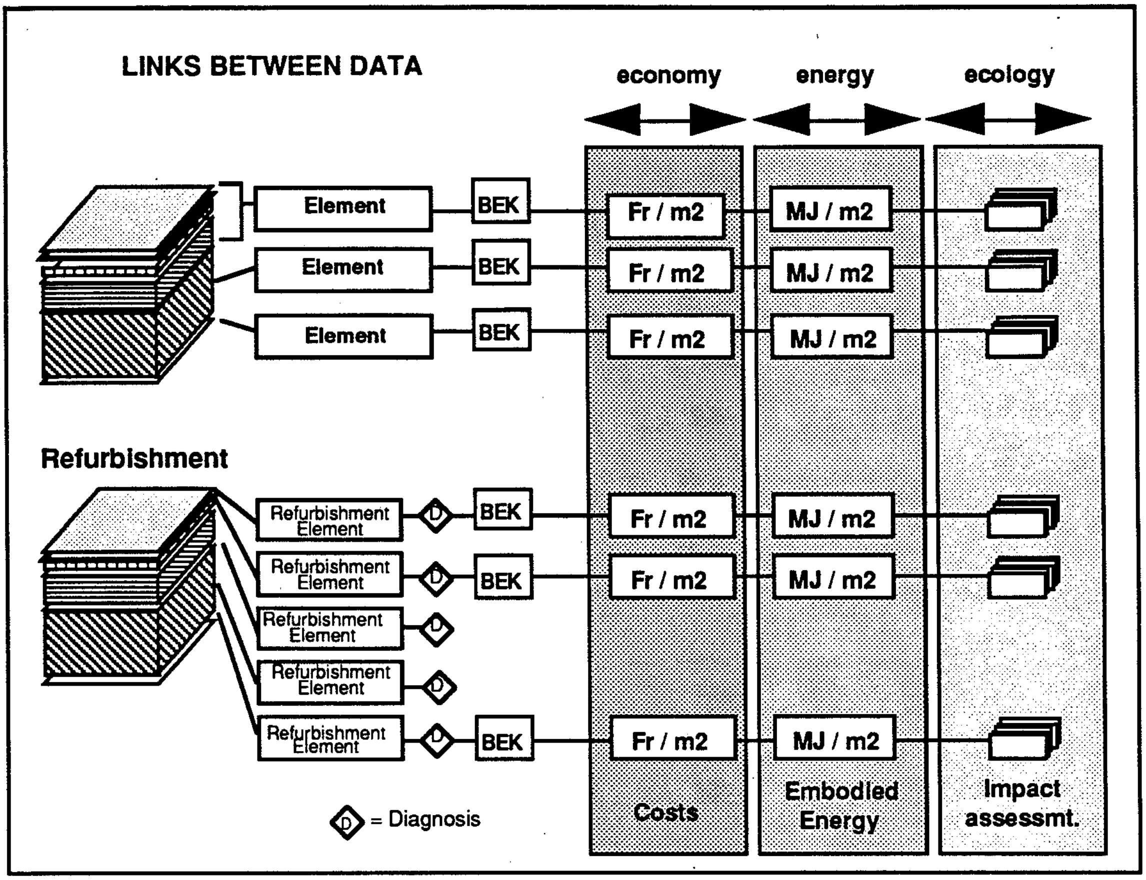


Figure 3: Links between financial, energy and ecological data [LUZ]

Until this database exists, the first estimation could be made according to emission risks (and not quantities emitted) during the different stages:

- ☐ Production of materials
- ☐ Production of components
- ☐ Construction of home
- ☐ Use
- ☐ Refurbishment
- ☐ Disposal and recycling

This evaluation will rely on the existing material declaration, product list and recommendation (labels).

Level 3: Production planning

At this level, the local impacts are considered. The performance defined in *Level 2* has to be achieved with the most appropriate technology (process and materials). The same element classification as at *Level 2* can be used.

The analysis will concern the impacts on the working conditions on site and on the user environment during operation. Questions about the use of prefabricated elements to reduce local impact (but taking into account transport) can be answered. In the case of refurbishment with tenants occupying the flats, these questions will become even more important.

Phase: production planning
Responsible: building direction (architect, engineers, entrepreneurs)
Specialists: constructors, technical coordinator

Instruments:
A distinction has to be made between the tender and the planning of the operations on site. The tender needs a precise definition of the construction process. The following aspects have to be considered:

☐ Dust
☐ Solvents
☐ Noise
☐ Sealing of ground
☐ Pollution of ground water on site
☐ Impact on fauna and flora on site

Elements (*Level 2*) are composed of materials and operations. The operations can be evaluated at this level (catalogues). Particularly interesting processes (producing little noise and dirt) could be documented in the form of Gant diagrams.

Planning levels	**Preliminary Work**	**Scheme Design**	**Detail Design**	**Production Planning**
Level 1	▨	▨		
Level 2		▨	▨	
Level 3			▨	▨
Prototypes	▨	▨		
External Costs	▨	▨		
Global energy balance		▨	▨	▨
Life cycle analysis		▨	▨	▨
Life cycle impact assessment		▨	▨	▨
Environmental impact ass.	▨	▨	▨	
Negative Lists			▨	▨
Product declaration			▨	▨
Product labeling			▨	▨

Figure 4: Use of planning tools at different levels [KOH92]

8.0 Building product models

The integration of new knowledge in the design process is limited by the planning structures as well as by the planning tools [IWC]. The actual computer aided design systems, being in fact rather computer aided drawing systems, proved to be inadequate to integrate non-geometrical data. The different specialized functions like energy simulation, cost planning, scheduling a.s.o. are executed by specialists with their particular software. Attempts to interface large amounts of specialized software have proven to be inefficient. The development of real CAD systems will need the development of building product models [GIEH].

The basic principles of product modeling come from manufacturing industries, mainly from the international STEP (Standard Exchange Procedure) efforts.

These models have to be useful in a top down process of progressive specialization (design process) as well as in an bottom up process by composition (production process). The point of departure is therefore the building in its final state ("as built"). All other states are derived from this state [BJO]. The development of a building product model for a building during its life cycle by using the STEP GARM approach is discussed in John Bedell's paper.

The advantage of these models is that the relations between different parts of the building, between different phases of its life cycle, between different design levels and between different approaches (points of view) can be modeled in the same way. Design becomes an activity with a possibility of anticipation by using default values and scenarios as well as specialization from the whole product to its basic components (taken out of nature or given back to nature).

These tools will not give the "definitive solution" which will never exist in the complex relations between a building, its use and the environment. They will allow a multitude of different points of view giving a possibility to judge which solutions fit best into a domain defined by a multitude of constants.

9.0 Conclusion

There will always be different points of view in the design, the construction, the use and the disposal of a building. The search for one universal aggregated coefficient covering all aspects makes no sense. Only design strategies using the existing knowledge in an optimal way (i.e., adapted to the planning process) will be successful.

Today, a comprehensive planning procedure will use different tools in different forms implying much adaptation between different planning levels and users. Tomorrow intelligent CAD systems, based on building product models, will allow a much higher degree of integration of knowledge and of cooperation between actors with different points of view.

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Methodological Principles for Life Cycle Impact Assessment (LCIA) of Buildings

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1.0 Introduction

The term "life cycle impact assessment" will be used in a colloquial sense in this contribution. The definition would be an inventory and evaluation of material and energy flows.

In German publications, the corresponding term "Oekobilanzen" is used as a generic term.

The analysis of material and energy flows to prepare measures to reduce, avoid or substitute production flows is not a new task. In the chemical industry, this activity is part of the general work of an industrial engineer. It is, however, generally limited to a process inside the factory or to a partial product.

For the description of production activities, the term "process analysis" is generally used. The attempt to analyze, to model and to evaluate material and energy flows has been extended to other objects under a growing environmental consciousness, this under the term "life cycle analysis".

Such an analysis is used mainly for packaging materials, but also in the building sector for whole buildings, building elements and building materials.

The new application gives rise to a few questions: To what extent can existing methodologies be applied in the building sector; what needs to be changed? And where do basic principles have to be decided on?

The integration of the life cycle impact assessment in the planning process and its relation to other methods such as product labeling are discussed in the paper of N. Kohler [Kohler].

2.0 What Can We Learn from Energy Analysis?

Energy analyses in the usual sense, i.e. energy flow models of the production of building materials as well as of the construction, use, maintenance and demolition of buildings have been established since the early seventies ([1], [2], [3]). In the same period, the first attempts were made to establish conventions for the methodology of energy inventories [4].

The reasons for and objectives of energy analyses in construction changed several times and varied in intensity. In the first phase, the objectives were purely scientific, then focused on the aspect of resource rarity and finally dealt with the problems of rising energy costs.

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After 1980, energy analysis was developed as a design tool adding new criteria to the financial criteria [5], [6]. The climax of this development was reached by the mid-eighties. Sinking oil prices reduced drastically all interest in these methods. The data concerning embodied energy of building materials elaborated during this period remain today the basis for environmental evaluation of building materials [7], [8], [9], [10]. The data resulted from individual work (Ph.D. theses etc.); they were often partial and not updated. The following conclusions can be drawn from these efforts:

- ☐ The collection of data through campaigns by individual scientists without any general accumulation or updating reduces the general acceptance of these data.
- ☐ The value of the data is reduced even more by the heterogeneous choice of system limits, which were generally not explicit or not consistent.
- ☐ Concerning system limits, the following issues were not clearly settled:
  - number and type of upstream processes to take into account
  - number and type of auxiliary processes to take into account
  - evaluation of import products
  - evaluation of recycling
  - evaluation of production losses
- ☐ Concerning the use of data, it is not clear if the best values or the average values have to be taken into account.
- ☐ Concerning the general data, there are large gaps in:
  - average data for the supply of final energy
  - average data for transport processes
  - average data for construction site processes
  - average data for whole groups of building materials (such as paints)

The use of non-renewable resources was expressed in energy terms in the form of feedstock energy. In this way, energy analyses could be enlarged. A building component realized in PVC would consume not only the direct energy for the production of the PVC and the production of the component in a factory (embodied energy), but also the combustion value of the oil used as raw material for the PVC (feedstock energy).

The author believes that this way of taking into account the use of resources was specific to traditional energy analyses and that the energy and material flow analysis of a process takes these aspects directly into account. It is no longer necessary to transform resources into energy units. On the contrary, each energy requirement can be traced back to its initial material (resource) flow and summed up within the general resource requirements of a process.

3.0 State of the art of life cycle impact assessments (LCIA)

LCIAs are established today for different types of objects. They concern processes, products, activities, firms or regions. For products, the best known LCIAs concern packaging materials [11]. The main objective of an LCIA is the assessment of global environmental compatibility of products, processes or activities. For the different clients additional objectives are:

- ☐ Environmental optimization of production processes
- ☐ Assessment of environmental compatibility of a new product or material

☐ Integration of environmental criteria into the decision process

☐ Improvement of corporate image, advertisement, public relations.

Even if there is a large demand for standardized LCIA methods, no generally applicable method has been established. During the elaboration of LCIAs, many new questions have arisen and combine with old questions (which have not found satisfactory answers) from energy analyses. These questions are:

☐ Uncertainty about the number and type of materials which have to be taken into account.

☐ Uncertainty about the additional criteria beyond energy and resource requirements, emissions and waste. Possible additional criteria are: heat dissipation, ionizing radiation, noise, sealing of soil etc.

☐ Uncertainty about the definition of a material as a pollutant

☐ Problems in distinguishing acquisition, allocation and evaluation of data

☐ Problems in distinguishing causes and effects

☐ Problems of allocation of inputs to products inside a firm

☐ Problems concerning the type of aggregation and the use of standard data sets for basic processes (see Leuridan).

In addition, there can be a conflict between the need to represent data in a LCIA and the product secrets of a firm.

The transition from energy analyses to LCIAs is a logical consequence. New problems arise through the enlargement but the holistic/comprehensive approach is at the same time a protection against partially optimized solutions. The experience gained in energy analyses can however be totally integrated in this enlarged approach and the conventions of energy analyses can be used extensively.

4.0 Possible solutions

The following proposals are based on work which the author has done at the LESO-EPFL [12], [13].

These proposals were elaborated for the Swiss Federal Department of Energy (BEW) and they are used as a condition for public subventions of LCIAs in the construction field. [14] focused on the application of the LCIA in construction.

4.1 Fundamental assumption

LCIAs can be used for different objects and in different contexts. The basic assumptions concerning the delimitation of the object, the delimitation in time and the delimitation in space constitute the LCIA-model.

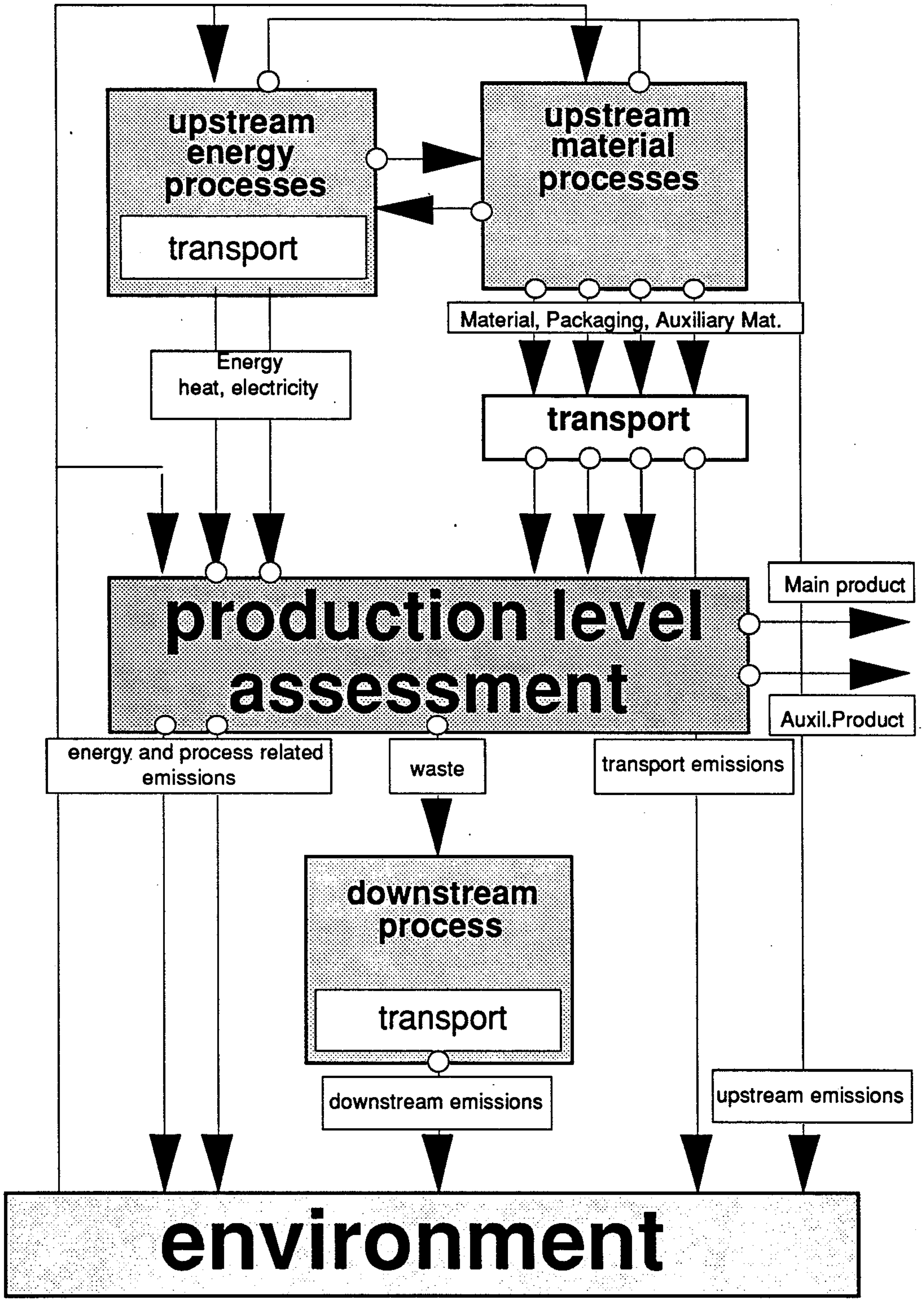


Figure 1: General system limits

4.1.1 Object

Objects of an LCIA can be divided into the following categories:

a) A region (town country, continent)
b) A firm
c) A process (or part of a process)
d) An activity (i.e. a service)
e) A product (material)
f) A technical solution of a functional unit (element)
g) A technical solution of a use unit (building)

LCIAs of regions (a) are not part of this contribution. LCIAs of firms (b) or processes (c) are taken into consideration as necessary basic data for LCIAs of activities or products. The result of the analysis of a firm has to be transformed into the data specific for a material. The data resulting from assessments of activities (d) such as transport processes and building processes and from assessments of products (c) are the principal topic of this contribution. The difference between the assessment of a technical solution (f) and a product (e) lies in the fact that the functional unit has to be maintained during its life-cycle. A functional unit in a building is an element like a window in its definitive place. A use unit, like a building, does not only have to be maintained in its function, it must also be operated during its life time (heating, lighting, etc.).

Other considerations concerning building product models can be found in Bedell's contribution [BEDELL]. The functional units and use units describe performances, whereas the technical solutions describe the constructive answer fulfilling the performances.

4.1.2 Time limits

The basic distinctions in assessments are: momentary, looking backward, looking forward. These distinctions are implemented in the stage model. This model distinguishes stages in production as well as in use: preceding stage (upstream), current stage, following stage (downstream). There are therefore:

a) Stage related assessments (momentary)
b) Accumulated assessments (momentary and upstream)
c) Life cycle assessments (momentary, upstream and downstream).

For products with a short life time, the life cycle assessment can be realized at the (physical) end of the life time. This is generally not possible for buildings. The assessment is generally established during the design stage and simulates the process of production of a building as the end of the construction process (looking backward). The other cycles are considered as forward looking scenarios. The indications concerning the operation of a building can be relatively accurate, the indications concerning the refurbishment, disposal and recycling are largely hypothetical.

It is of course always possible to limit the considerations to other intervals like time of effective use, life time, etc.

4.1.3 Space limits

Independent of the object, the space limits of the assessment of the preceding and following stages have to be fixed. The following levels can be used:

☐ Regional
☐ National
☐ Continental
☐ Global

If processes are not included within the limits, an exchange function (e.g., for import/export) can be used. The author proposes a global approach where all energy transformation, resource requirements and resulting emissions are recorded at the place where they occur and introduced into the assessment. The particular situation of the considered place (where the house is built) has no influence on the balance aspect of the assessment but on the aggregation/evaluation aspect.

4.2 Division of work and Procedure

From the shortcomings of energy analyses due to the campaign character of individual data acquisition and the lack of updates, the author proposes a new division of work concerning data acquisition. The basic assumption is that only industries (with their own personnel or by hiring the services of a consulting firm) can proceed to a reliable and realistic data acquisition as well as its update.

The acquisition takes place in the individual firms. One should not demand too much of them; they should basically handle only the data which they already know and allocate these data to their final products. These data concern material and energy flows across the limits of the firm (input, output) as well as flows and different processes inside the firm. The individual firm will establish which quantities of energy are used in the process but not how much energy or emissions have been used in upstream processes, e.g., for the preparation of fuel or electricity. The industrial branch organizations should establish average values for typical products (e.g., for bricks, cement) and also update these values as necessary.

The proposed division of work implies the need to dispose of so-called basic data sets on a national or continental level concerning:

☐ Energy supply
☐ Transport processes (outside the producing firms)
☐ Disposal processes
☐ Basic materials.

These basic data sets have to be managed and updated on a higher level. For the moment, necessary structures do not exist, even if partial attempts have been made in the industrial energy consumption in Switzerland for instance. There is a need for a large collaboration between science, industry and government to fix the necessary system limits and to establish general conventions concerning data acquisition and management.

The persons working on LCIAs should mainly manipulate existing data and evaluate results. In practically each task, data provided by the industry will have to be linked to general data sets. Furthermore, the integration of level related data into life cycle analyses will need to respect rigid conventions and rules in building the scenarios.

Concerning the detailed procedure of establishing LCIAs, there has to be a very clear distinction between data acquisition and data evaluation. Of course, even the choice of the domain of data acquisition is already a first evaluation.

The data acquisition procedure can be subdivided into 4 activities:

a) Representation
The material and energy flows inside the system limits of the client are represented. These data are usually internal to a firm.

b) Allocation
The flows represented inside the system limits of the firm are allocated to the end or intermediate products. The main task is to distribute correctly the energy inputs, the resource input, the emissions and waste among the products and the services which leave the firm.

c) Links
The product-related inputs and outputs of the firm have to be linked to basic general data sets for energy preparation and transformation, transport processes, disposal and basic raw materials. These basic data sets represent the upstream and downstream impacts on the environment provoked by the specific production. From this step result the LCIAs for products at different levels (production stage, accumulated stages or life cycle).

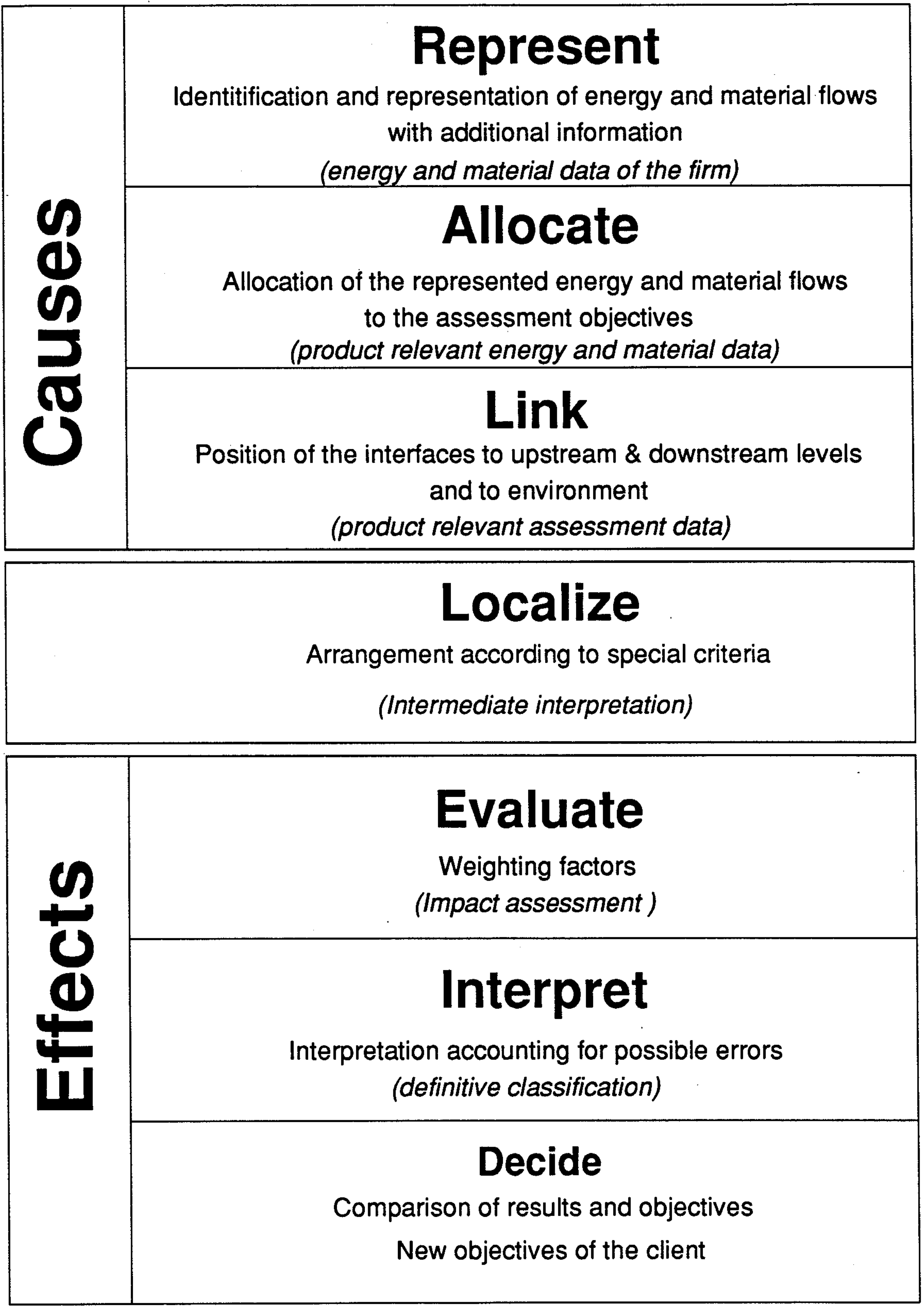
d) Localization
This activity constitutes a first analysis of the data without a real evaluation. The data are arranged and presented according to specific criteria. The objective is to identify inside the firm the main problems related to specific emissions or combinations of emissions. It is not possible at this level to appreciate for instance the impact on water or air which is part of a specific evaluation. The localization allows, however, first conclusions concerning strategies to avoid certain emissions or wastes or to reduce the energy and resource requirements.

4.3 Quality of data

As long as there are not sufficient reliable data from LCIAs and centralized databases, one will be obliged to use data from literature or default values as hypotheses. It is crucial to indicate in all LCIAs which type of data has been used. The author proposes the following classification:

a) Measured values
These data are provided by measurements in the production.

b) (Minimal) legal values
These values are prescribed by the law and they generally reflect an average existing technology. They are independent of a particular product and they can be used for comparisons of current technologies.



Represent

Identitification and representation of energy and material flows with additional information

(energy and material data of the firm)

Allocate

Allocation of the represented energy and material flows to the assessment objectives

(product relevant energy and material data)

Link

Position of the interfaces to upstream & downstream levels and to environment

(product relevant assessment data)

Localize

Arrangement according to special criteria

(Intermediate interpretation)

Evaluate

Weighting factors

(Impact assessment)

Interpret

Interpretation accounting for possible errors

(definitive classification)

Decide

Comparison of results and objectives

New objectives of the client

Figure 2: Assessment procedure

c) *Synthetic values*
These values are based on physical or chemical calculation. They represent basic requirements of a process without any preceding or auxiliary process.

d) *Values from literature*
They are problematic because the system limits are rarely indicated clearly.

e) *Average values*
If a product or activity results from different firms and/or different technologies, an average value has to be calculated.

f) *Best values*
They can represent the trend of a technological development and be used as a basis for forecasts.

g) *Prospective values*
They are used as a basis for scenarios.

The transparency of all LCIAs has to be assured by the qualification of the data. A possible weighting would be:

Measured average value	1
Measured single value	2
(Minimum) legal value	3
Value from literature	4
a.s.o.	

In an update, the improved reliability of data could be expressed in this way.

4.4 General system limits

Certain general system limits are recommended below. More detailed recommendations figure in [12] and [13].

a). Limit and number of criteria to be considered
An environmental model should in every case take into account the use of energy relevant resources (rare or non-renewable resources) and the impact on air, water and soil of the primary emissions. For the emissions, the values after the filters are considered emissions into the environment. In the case of external disposal, the values are also taken after the filters of the centralized equipment. The number of emissions to be considered is fixed by federal regulation.

b) System limits for a single firm (stage)
In general the direct inputs and outputs (energy and material) of the firm are considered. This also refers to auxiliary processes such as administration, repair shops etc. The requirements for the construction of the buildings and the production of the machines are not taken into account. The only exceptions are made when comparing different energy transformation techniques (e.g., nuclear power plants, solar cells etc.).

Requirements for the reconstitution of human work are not taken into account.

c) Physical content and inherited content
The allocation of potential emissions to a product continue to be linked to this product, even if it is transferred to another user/owner. The potential emissions are inherited and will be under the responsibility of the following user.

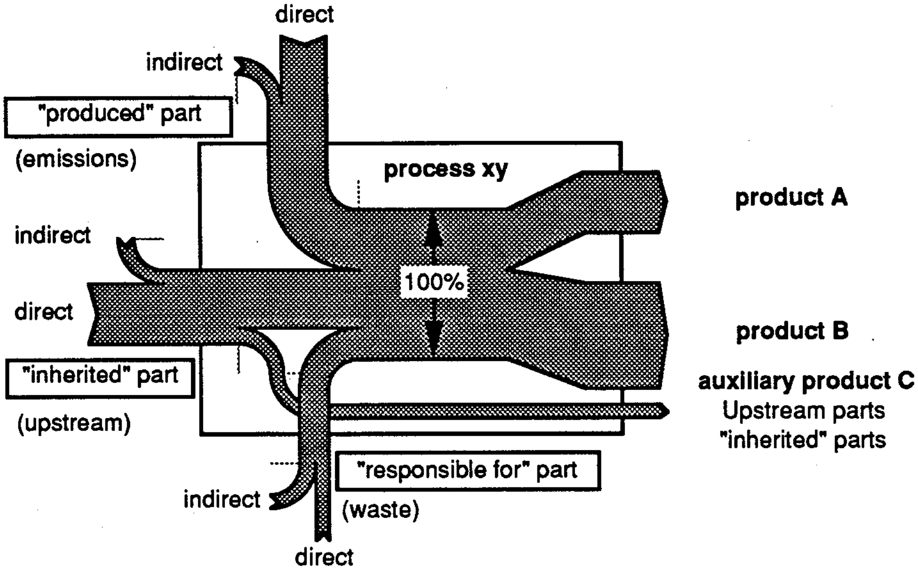


Figure 3: Produced, inherited and responsible part in a product

d) Bonus
All bonification is not refused. This is particularly important in the construction field, where the time lag between production and recycling can be very long. It is in this case possible to subtract possible recovered energy in recycling from the necessary first energy requirements. The possible recovered energy can be indicated as given information.

e) Transport
The transport of production waste is charged to the producer of a product. All other transport is charged to the purchaser from the point of purchase. Energy is considered "existing where used". The transport of goods is accounted for in "tkm" of a particular transport agent (truck, train, etc.).

5.0 Data for Inventories of buildings

In the building and construction sector there is a need for additional general data sets concerning:

- ☐ Primary building materials
- ☐ Construction processes (in factory and outside)
- ☐ Scenarios for maintenance and refurbishment
- ☐ Scenarios for demolition and recycling
- ☐ Specific emissions from building elements during their lifetime (which can be harmful for users).

In the described building model [BEDELL] and planning tools [KOHLER] the central importance of the building element as a basis for data structures appears. These elements represent technical solutions of defined functional units. They include constructive solutions in their definite place in the building and recognize all necessary upstream processes for energy supply and material, transport and construction processes. The data structure is compatible with the data structure for cost calculation. Furthermore, the implications for possible recycling, emissions during use, maintenance and refurbishment possibilities are not determined by the material alone but by the position of elements in relation to other elements and the building in general. Other considerations concerning the relation between economy, energy and environment related data in the building process can be found in [15].

6.0 Perspective

The basic principles for LCIAs exist today. The main task today is the implementation. Another problem lies in the establishment of a broad, updated and independent database. This task is continental and goes far beyond the building industry. There is a need for conventions for general system limits to assure the compatibility of data. There is a reasonable prospect of soon obtaining reliable basic data sets for energy, transport and disposal processes. In the building field efforts should concentrate on:

☐ Analysis of construction processes on site
☐ Recycling rates of typical elements
☐ Direct emission of typical elements during life cycle
☐ Selected building materials (paints, glues, sealants etc.).

The author plans to work on methodological questions and to coordinate the existing scientific potential of the Hochschule für Architektur und Bauwesen, Weimar, in the field of material science and life cycle impact assessments.

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Environmental Evaluation Methods Based on Energy and Material Flows as Applied to Buildings

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1.0 Introduction

The construction, operation and demolition of buildings use large amounts of raw materials, manufactured components and energy in different forms. These flows of material and energy during the lifetime of a building produce significant emissions and releases of both mineral and organic substances into the different domains of the biosphere, thereby interfering with natural biological and chemical cycles.

These flows induce the main environmental impacts in the building process; this is why they have to be known from the start of every type of valuation. The enormous quantity of data which the knowledge of the principal flows produces makes their appreciation very difficult. The particular valuation methods which have been developed are therefore always aggregation methods, i.e. they try to reduce and weight the information given by the flow analysis.

The first attempts to formalize valuation methods were made in the field of packaging materials. The basic aim of the methods under development at present is to compare products, mainly consumption products. These methods do not take into consideration the exact location of emissions; they are independent of the site and to a certain degree independent of time.

The main objective of this contribution is to analyze the existing aggregation techniques and to judge whether they are suitable for the valuation of the impact of buildings on the environment. It is, however, clear that it is insufficient to consider only these general aggregation techniques; the construction of a building has consequences on the environmental equilibrium at the site of its construction. Therefore specific criteria have to be taken into account which are related to the site. This aspect is treated only briefly in this contribution.

Figure 1 illustrates the general approach. The central object of the contribution is printed in bold face: the evaluation by aggregation based on energy and material flows.

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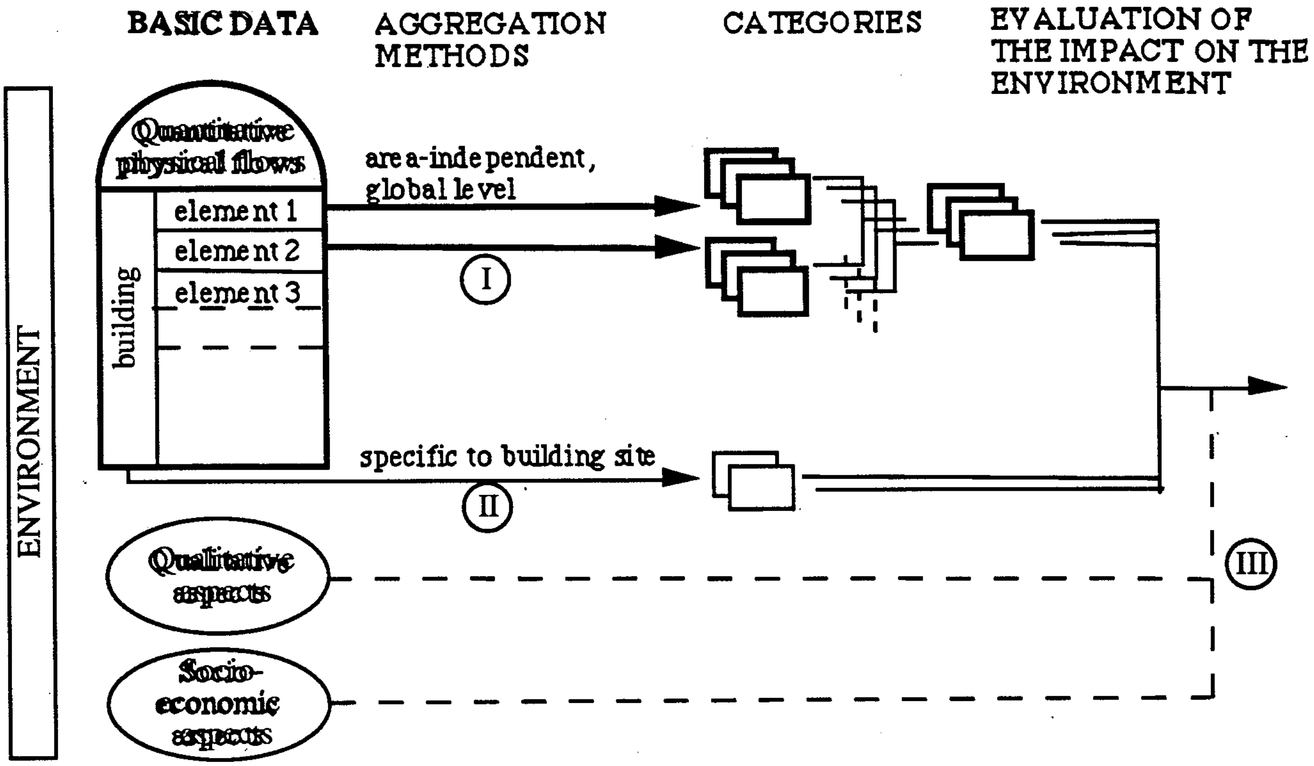

Figure 1 Aggregation methods in the general context of environmental impact assessment of a building

2.0 Aggregation methods

2.1 Global methods, site independent

2.1.1 Terminology and general approach

According to the terminology used in life cycle assessments, most aggregation methods are not by themselves evaluation methods. In particular effect-oriented approaches are based on a strictly quantitative analysis of environmentally relevant processes.

Each evaluation can be divided into three successive sections [Assises, 1991] :

- ☐ The inventory
- ☐ The classification
- ☐ The evaluation

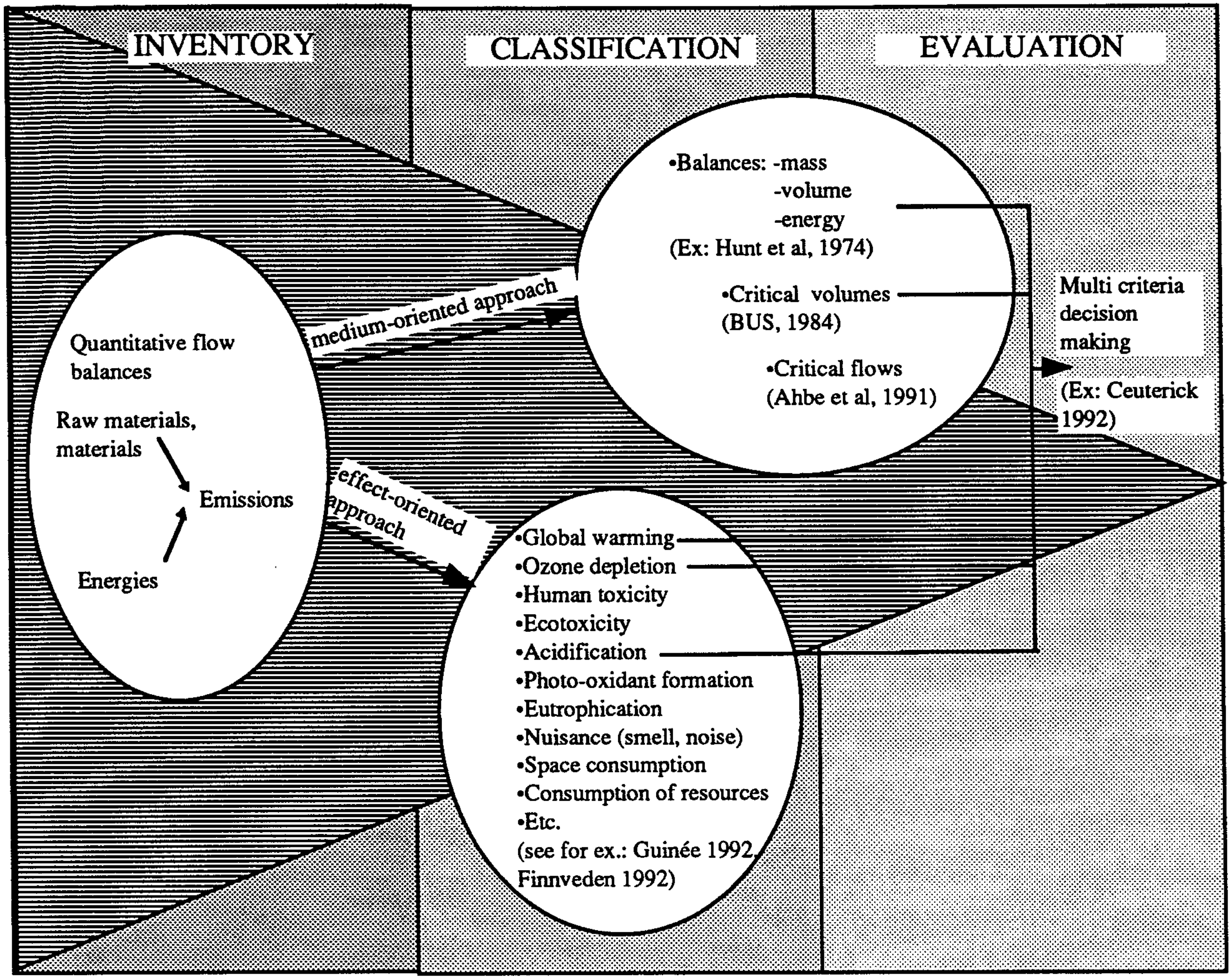

Figure 2: Data and methods of aggregation

The balance of the different flows constitutes the inventory. The inventory section can be defined as [Fava *et al,* 1991): "an objective data based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases throughout the life cycle of a product, process, or activity".

The classification is defined as the aggregation of impacts to the environment based on a scientific analysis of the relevant environmental processes.

The evaluation is the final stage of aggregation. At this level a real evaluation based on the aggregated impacts (classification) is implemented. As an illustration one could say that at this level we add "apples and oranges". A final evaluation must often take qualitative and socio-economic aspects into account, considering, for example, such different impacts of a product as its contribution to global warming and consumption of land, its esthetic and socio-economic effects on a region, etc. In this regard the study of Ceuterick *et al* [1992] concerning the impact of the production of insulation materials is interesting (see *Figure 2).* On the basis of the results of several aggregation methods, the final evaluation was implemented by using a multi-criteria decision-making method (Promethee).

The following description of aggregation methods distinguishes two categories: the medium-oriented approach and the effect-oriented approach. This paper, with no claim to exhaustiveness, presents the general principles governing these methods.

2.1.2 Medium-oriented approach

The medium-oriented approach groups methods with categories defined by emission areas. The critical volumes method, for example, is based on three domains: air, water and soil; all parts of the environment affected by emissions.

1) Mass, volume and energy balances

One of the first approaches was the one by Hunt *et al* [1974]. The following seven categories were used:

☐ Atmospheric Emissions	[kg]
☐ Waterborne Wastes	[kg]
☐ Industrial Solid Wastes	[m^3]
☐ Post-consumer Solid Waste	[m^3]
☐ Raw Materials	[kg]
☐ Energy	[J]
☐ Water	[l]

All emissions[12] were considered equally important; the aggregation was performed without weighting.

This can also be considered as an indicator method. An aggregation without weighting risks giving erroneous results. Nevertheless, these rough methods can prove useful in a certain methodological context. In fact, if it is possible to identify indicators leading to the same average classification as other, more complex methods, then these indicators can serve as general indicators.

Furthermore, indicators such as total material flows and primary energy or total energy (aggregated not from the output efficiency of energy transformation of the different agents but from environmental criteria), allowing a first general evaluation without determination of emissions, can be used in intermediate rough analyses.

2) Limits for emissions

a) Principles

This model aggregates the data given in material and energy balances in relation to the domains of water, air and soil. The emitted substances are weighted with their respective emission limits before they are added up.

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[12] Emissions group all substances which are emitted during the production, utilization or disposal process. Emissions are not identical with pollutants. Pollutants are substances which are legally recognized as of toxical nature.

$$\sum_{\text{per domain}} \frac{\text{Emission substance i [gr/product]}}{\text{Emission limit [mg/m}^3\text{ or l or kg]}} = \left[\frac{\text{m}^3\text{ or l or kg}}{\text{product}}\right]$$

We thus obtain three values (one per domain) with a fictitious volume or weight:

☐ Critical air volume	[m^3]
☐ Critical water volume	[dm^3]
☐ Solid waste	[cm^3]

The more a product pollutes, the greater the calculated weight.

b) Principal advantages and disadvantages of this method

This method is transparent and can be applied without difficulties. Emissions in water are not added up with gas or solid emissions.

There are only a limited number of substances with an emission limit (about a dozen in Switzerland). This is why certain authors performed interpolations from MAK values (maximum concentration at the place of work) to increase the number of limit values, which are no longer necessarily established under strictly reproducible criteria. These limits can differ from one country to the other. The method in question does not consider dispersion phenomena, nor the lifetime of the emitted substance.

c) Derived methods

☐ Schaltegger *et al.*[1991] proposes to define emission limits with a unit which is common to all three domains: the mole.[13]

This procedure allows:

- Standardization of the emissions of the different domains (water, air, soil)
- Definition of the emissions by their "particle concentration"
- Avoidance of the considerable distortions existing with other units (kg, l, m^3) in case of temperature fluctuations, for example.

The principal aggregation problem between categories remains however.

☐ Hofstetter [1989] proposes to standardize the three results "critical air volume", "critical water volume" and "solid waste" by weighting them respectively with the air volume, the precipitation and the soil weight observed on a unitary soil surface (1 m^2). They can then be added up and a result of a single value can be obtained. However, as in the previous method, the final aggregation of the results in the three domains is methodologically unsatisfactory.

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[13] A mole is a unit quantity of material containing $6.023*10^{23}$ molecules. The number was determined by Avogadro on the hypothesis that equal volumes of different gases contain the same number of molecules.

3) Material flows

a) Principles

This method uses the notion of "ecological scarcity" which is the relation between the present material flow of man-made origin (F) and a critical flow (Fk). This relation can refer to emissions or to resources. Two types of critical flows (capacities limited by nature) can be distinguished:

- ☐ The cumulative scarcity which concerns non-renewable resources
- ☐ The marginal scarcity which expresses the capacity of nature to absorb a certain quantity of material flow (e.g., the self-cleaning capacity of a river).

The relation between F and Fk can take several forms. It can be logarithmic (similar to lethal curves to evaluate the effects of toxic substances), parabolic or linear (expressing the superposition of different curves of toxicity).[see BUWAL, 1990, p 20-23]

For a linear relation between F and Fk (F/Fk) the quotient F/Fk is called the ecofactor.
Ecofactor = 1/Fk * F/Fk * C [ecopoints/gr of emitted substance].

The calculation for each substance (under the condition that the critical flow is known) allows determination of the environmental value of a product (ecopoints) :

$$\sum_{\text{for a product}} \text{Emission substance } i \text{ [mg]} * \text{Ecofactor of the product } i \text{ [ecopoints/mg]} = \text{[ecopoints]}$$

Comments:

- ☐ The domains taken into consideration are air, water, soil and energy
- ☐ The flows F and Fk are defined for a given geographical space in tons per year (for air, water and soil) and Tera Joules per year (for energy)
- ☐ This method can be considered as an optimization method
- ☐ About 20 ecofactors have been calculated for Switzerland by now. There are attempts to extend this list for Switzerland and to establish ecofactors for Europe as well as prospective ecofactors for probable future emission flows.

b) Advantages and disadvantages

The method gives one value as a result and accounts for the scarcity of natural resources and the capacity of nature to provide renewable resources and to absorb emissions.

On the other hand the critical flows are difficult to determine and they may appear arbitrary. They depend on technical possibilities and on political and economical objectives. This method has a strong normalizing character and the basic data needs are considerable. At the moment the critical flows have been established for few substances. The aggregation of emissions into air, water and soil is *a priori* doubtful. Ecofactors have to be continuously adapted to take into account the evolution of an emission of a substance. Dispersion and convection effects are not considered.

c) Derived methods
Hofstetter [ETHZ, 1991] proposes to use the flows of natural materials as weighting factors instead of the defined critical flows (Fk). The disadvantage of this method is the impossibility of accounting for the flows of synthetic materials which do not exist in nature.

2.1.3 Effect-oriented approach

The effect-oriented approach groups methods with categories defined by the effects which different emissions can cause.

1) Principles
When the effect has been chosen and carefully defined the next step is to quantify the contribution of different substances to the effect. This should result in some conversion factor, which describes the contribution to the effect at hand per amount or mass of emitted substance. Then by multiplying the emitted amount or mass by the conversion factor the contribution of the effect by the substance is estimated. By adding the contribution to the effect from different substances, the total contribution to the effect from the product or process or whatever the object under study is, can be estimated. [Finnveden *et al,* 1992]

The list of indicated categories of effects is not exhaustive. It depends on the product to be evaluated and on the principal impacts on the environment which it is likely to cause. As an illustration, two effect-oriented methods are described in more detail: global warming and acidification. For more information on these methods, examples and on other categories such as those mentioned in *Figure 2* (see [Finnveden *et al*, 1992] and [Guinée, 1992]). The different effects are not treated in an identical way in all methods and the conversion factors for one effect can change from one author to another.

2) Global warming
The so-called greenhouse effect is caused by the release of certain gases (trace gases) into the atmosphere. Absorption of the outgoing radiation and re-emission of the infrared heat radiation towards the earth causes the temperature at the surface of the globe to rise. In assessing the contribution to radiation from trace gas emissions there are two properties of the trace gases which must be considered:

☐ The atmospheric lifetime of the trace gases
☐ The absorption properties of the trace gases

On this basis a simplified method can be elaborated to describe the expected climatic effects from emissions of greenhouse gases. IPCC (*Intergovernmental Panel on Climate Change*, WMO, Geneva) presented the concept of Global Warming Potentials, GWP, defining it as "..the time integrated commitment to climate forcing from the instantaneous release of 1 kg of a trace gas expressed relative to that from 1 kg of carbon dioxide"

$$\text{Global Warming Potential} = \frac{\int_o^t a_i * M_i * dt}{\int_o^t a_{CO_2} * M_{CO_2} * dt}$$

Where,
a_i is the relative absorption coefficient and M_i is the atmospheric lifetime.

It is possible to calculate conversion factors (GWP) for all trace gases which contribute directly (CO_2, CH_4, N_2O, CFC-x, HCFC-x; etc.) or indirectly (CO, NOx, NMHC, CH_4) to the greenhouse effect. The time horizon generally chosen for the integration of the temperature effects is 100 years.

The result expresses a potential impact, describing the extension of the emissions contributing to the greenhouse effect, and not the real impact.

3) Acidification

For acidification, acid deposition to soil and surface water is the endpoint of the classification. Acid deposition can be calculated in terms of potential H^+-equivalents. Acidifying emissions of SO_2, NO_x and NH_x can be aggregated based on their potential to form H^+. Analogous to GWP, an acidification potential (AP) can be developed. The AP can be defined as the number of potential H^+-equivalents (H^+_i) per mass unit of substance i (m_i) compared to the number of potential H^+-equivalents(H^+_{ref}) per mass unit of a reference substance (m_{ref}): sulphur dioxide (SO_2).

$$AP_i = \frac{\text{potential } H_i^+/m_i}{\text{potential } H^+_{SO_2}/m_{SO_2}}$$

This expression is suitable for a global evaluation. The equation takes into account a dose factor: the potential H+ equivalent, which indicates only the dose which can be supported by a particular environment. In a more site specific classification it might be appropriate to add an effect factor - for example, for toxicity of this factor might be based on so called “no observed effect levels” (NOEL) - integrating in the equation so-called “critical loads” of H^+. Recently developed [Hettelingh *et al.*, 1991), the critical load is the quantity of acid deposition which an ecosystem can bear without changes in the chemical composition of soil, water or needles resulting in ecosystem damage.

One of the major problems of these methods is to clearly identify an environmental problem and to find its exact causes which have to be expressed in the form of emissions. A cause-effect relation has to be identified. This can generally be done by modeling the “future” of emitted substances (transport, dispersion, transformation, deposition, absorption, etc.)

2.1.4 Conclusions

The different evaluation and aggregation methods can be described by the following expression:

$$\sum_{i=1}^{n} \text{emission}_i * \text{weighting factor}_i$$

Where,

- ☐ *n* is the number of emitted substances per mass unit of the considered product
- ☐ emission$_i$: is the quantity of the emitted substance caused by the considered product
- ☐ weighting factor which relativizes the impact of the substance *i* on the environment in relation to other emitted substances, allowing aggregation of these emissions.

These methods are therefore in most cases:

☐ Limited to quantitative physical or biological flows

☐ Based on the hypotheses that the emission-effect relation is linear

☐ Independent of the site and the moment of emission. There are therefore more hazard assessments than risk assessments.

In conclusion, these methods do not describe the real impact of a product on the environment. The result can only be interpreted as an absolute value, permitting comparison only at a global level of the considered product and other products.

2.2 Site specific methods

In the life cycle impact assessment literature there are few aggregation methods related to the evaluation of the emissions produced on the site of construction of a building. In this section we describe only some categories which could be used in an analogous way to the aggregation methods with a global level. The principal distinction would be that with the site specific methods the location is taken into account and in some cases the real effects on the environment are considered.

According to the endpoint, specific aggregation methods could be developed for the appreciation of the impact of a building on its immediate environment. Possible categories are:

☐ *Modification of the hydraulic equilibrium:* The construction of buildings, car-parks and roads modifies this equilibrium locally. As a consequence of the sealing of the natural soil there can be overflows and reduction of the ground water level.

☐ *Micro climate:* The heat dispersion can be changed and the albedo of the ground can influence the local climate.

☐ *Consumption of the territory:* The impact is different according to the quality and use of the soil.

☐ *Destruction or division of ecosystems:* A building by its implantation and the induced human activities can influence the existing ecosystem more or less. The effect depends on the sensitivity of the concerned ecosystem.

☐ *Noise and odors. They depend on the function of the building:* There has to be a distinction between direct emissions (noise of the ventilation equipment of a building) and induced noise (caused by traffic activities induced by the building).

☐ *Influence on the users of the building and/or the workers on the building site* (toxicity of the materials, allergic potential).

☐ Etc.

Without going into much detail, it is clear that this approach is particularly important for the evaluation of a building. The main difficulty here will also be the identification of the relations between causes (emissions) and effects (impacts on the environment).

3.0 Objectives of the research

Our main objective is to identify one or several global aggregation methods or better one or several indicators which might serve as reference tools for the evaluation of the impact of any building on the environment during its life cycle. To achieve this aim, we will model in detail a large number of fictitious buildings [Bedell and Kohler, 1992] and apply to them the existing aggregation methods. With an analysis of principal components, it will be possible to calculate an average method. Then, we will proceed to create first a more complex situation and then reduce this complexity again.

The second objective is to establish categories allowing evaluation of the impact of the building on its immediate surroundings. The simulated buildings will allow us to test the sensitivity of these methods and to foresee the principal impacts on the environment caused by flows related to the site of the building. A number of these flows are exogenous to the building, road traffic caused by the building being just one example.

3.1 Global evaluation of buildings by elements

Given that there is not a single best method and that the real impact of a building on the environment is not known, the methods with a global level, without location of emissions and effects, are applied as follows:

- ☐ A number of fictitious buildings, which are nevertheless representative of the Swiss building stock, are modeled.
- ☐ The mass and energy flows are calculated for every building, taking into account the five constitutive phases of its life cycle: extraction and preparation of raw materials and final energy, construction of the building, its use, renovation and elimination.
- ☐ The emission flows are calculated from data sets[14] of material and energy flows.
- ☐ Application of several aggregation methods.
- ☐ Calculation of an average method weighted by analysis of principal components[15].
- ☐ This average method will be based on one or more aggregation methods. The methods which give extreme results in comparison with the average method are excluded.
- ☐ Research and determination of one or more indicators by simple or multiple regression of the parameters used in the average method.

First, this procedure should explain the origin of the main pollution factors related to the consumption of raw materials and fossil fuels. This can lead to a list of recommendations which allows reduction of the emissions related to the construction of a building and the choice of building materials.

Second, the calculated method can then serve as a tool for the environmental evaluation of a building. To obtain environmental information in the design stage, material and energy flows per construction element are evaluated. More pragmatically, this approach could easily be performed by completing the "catalogues of the construction costs per element" (Elementkostengliederung CRB) with their environmental "notes".

When estimating costs, the architect can then also take into account environmental criteria in the preliminary design phase of the construction of a building. Thus, an optimization process can be established between the economic and the environmental aspect. It should be recalled that the environmental aspect is only a function of the chosen construction elements and of

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[14] The data sets bring the following processes into relation with the emissions provoked by them: materials, installations, transport, provision and burning of fossil fuels, elimination techniques.

[15] This analysis will be performed on the matrix of correlations of aggregation methods. The weighted average is calculated on the basis of obtained vectors.

the global conception of the building and does not give any information about the reasonableness of the building site choice.

3.2 Evaluation of buildings related to the site

The evaluation of a building through consideration of its impact on the surroundings can give answers about the reasonableness of its construction at a given site. Is it correct to construct a residential building with "ecological materials" but far away from work places, without public transport facilities?

It is important to take such criteria into account. The methodological approach of categories defined by the building site can orient itself to the approach elaborated for evaluation methods with a global level: determination of mass and energy flows related to the site, then emission calculation and aggregation of these flows according to various oriented approaches.

The evaluation of the results from different aggregation methods will certainly not allow retention of one or two methods indicating the final impact, as the approaches are too diverse. It will therefore be necessary to use a multi-criteria analysis method to obtain a single result.

On the other hand, the analysis of different scenarios can also lead to the elaboration of a list of recommendations. This list could, for example, recommend a minimal impermeability coefficient which would be economically sustainable, depending on the construction type. This evaluation relates to a site; it thus considers the building as a whole and in its context (see *Figure 1*).

3.3 Methodological problems

As the general methodological approach of an environmental building assessment can be criticized, there are also other problematic aspects:

☐ The quality of the basic data - mass, energy and emission flows - constitutes a real problem today. The evaluation might even be totally incorrect, for the following reasons:
  - Limits of the inventory system
  - A lack of data about certain construction materials and processes
  - A lack of homogeneity among the data themselves
  - Incomplete emission lists, in particular with regard to materials which cause emissions of very polluting substances
  - The approximation of emission coefficients. Given in grams and milligrams per kilogram material or fuel, these coefficients are multiplied by annual consumption quantities which can very easily amount to tons. In this way, imprecision can quickly get out of proportion.

☐ The incomplete correspondence of the emission list with the aggregation methods
  - The declared substance groups in emission lists do not necessarily correspond to those used in aggregation methods
  - It can happen that emissions by some processes are not considered in any method
  - The aggregation methods favor incomplete emission lists.

☐ Is the evaluation of a building by construction elements satisfying?

- The choice of "ecologically reasonable" construction materials offers no guarantee whatsoever that the building itself will also be "ecologically reasonable"
- How to integrate certain emissions which only emerge during the use of the building and which are not exclusively due to a construction element?

☐ Certain specific aspects of a building make the evaluation rather complex.
  - Compared to packaging materials and consumption goods, a building has a long lifetime, during which certain elements have to be replaced. Taking this into account makes the task more difficult. It is necessary to:
  - Well integrate all emission flows appearing during the use of a building, a phase which can predominate in the global environmental assessment, even if the data about this period rely largely on plausible scenarios
  - Maintain a certain transparency despite the great number of data
  - Take into account future possibilities of construction waste removal
  - Work, in general, with hypothetical scenarios.

4.0 Conclusions

Let us assume that we have before us two construction variants. One is in compliance with environmental criteria, but is costly; the other is cheaper, but uses materials considered to cause more emissions. This simple example shows that aspects other than those based on biological and physical flows also play a role in the evaluation of a project. These aspects may be (see *Figure 1*):

☐ *Qualitative*. One may think of the aesthetic aspect and the comfort of a building.
☐ *Socio-economic*. For example, the need for housing and for the development of new economic sectors
☐ etc.

Likewise, these aggregation methods do not constitute an optimization procedure as such. We propose to use them during the building design procedure by elaborating the evaluation of the material and energy flows of a building per construction element, but the questions about the principal preliminary decisions (the need to construct the building, etc.) are not answered.

Therefore, we must place these aggregation methods, still for the most part under development, in the context of a more complete evaluation and include them in the successive stages of decision and negotiation in the construction of a building.

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A Hierarchical Model for Building Costs*

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Abstract

The expansive domain of Kohler's project for estimating building costs requires unconventional approaches to data representation. A building decomposes into standard element categories in turn consisting of ingredients and ultimately a set of basic resources. The pyramid of production steps leading to the final building is represented as a hierarchy of the Functional Units and Technical Solutions derived from ISO-STEP's General AEC Reference Model. These form an evaluable structure of units calculating the economic, environmental, and other costs incurred by the construction, use, maintenance, and demolition of buildings. Related application models are similarly hierarchical; all share a common foundation with similar topological configurations of easily connectable, encapsulated subassemblies in a single unifying structure.

1.0 The Challenge of Building Costs

A building's construction and its ensuing use, maintenance, modification, and eventual demolition form a gargantuan collection of complex and expensive processes rendered only more formidable by recent increased attention to the environment and to resource consumption. Of those applications made feasible by improvement of representative models for buildings, the ability to forecast the costs of these industrial procedures, and so choose intelligently among alternative solutions, has perhaps the greatest immediate practical value. Its achievement over the next few years will entail new challenges, two of primary importance:

- ☐ Information technologies will be used more and more in all stages of design, production, use, and recycling of a building, but integrated tools will be lacking. Data management will be the central issue.
- ☐ The usual decision criteria affecting investment costs will be augmented by new post-construction costs (exploitation, maintenance, refurbishment, recycling), the consumption of energy in all its forms (direct and embodied), and the impact of these new factors on the environment.

These two challenges are strongly linked. It is impossible to know the life cycle costs without integrated data management tools linking the different phases of conception, realization, use, and recycling.

All existing life cycle cost models reflect the objectives of the owner of the equipment. They take into account only "real" costs which have to be paid. However, it is clear that the real overall cost of any item is much larger if we take into account the social costs associated with production, use, and disposal: the reduction of natural resources, use of public facilities, pollution of all kinds, noise, sickness, accident, and destruction of natural and urban scenery.

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These are considered "external" costs in economic theory [HOHM88] because they are not charged to the user of a piece of equipment but are accounted for by society (and hence are also called "social" costs). Our objective, to establish a broad and systematic approach to life cycle costs of buildings, immediately raises two difficulties:

- ☐ The description of a very complex system involving many aspects of human activity within the environment: chemical cycles, organisms, water, soil, air, energy, information, and material flow.
- ☐ There is no established way to "measure" the life cycle costs as an accountant calculates the financial costs of any item and then compares the calculated and actual money flows.

Whatever is done will rest on the level of a model, a very simplified representation of reality. Of course some of the inputs of the model can be quantified and measured, as can some of the outputs also, but the non-measurable inputs and outputs will predominate [KOH91a]. Furthermore it will not be possible to construct one overall model to answer all questions. There will be a spectrum of different models (of a building, the environment, economic factors, etc.) with different types and levels of precision. These models will, at least for the moment, be only loosely connected. The basic objectives of all models will be to:

- ☐ Describe different processes in a similar way.
- ☐ Identify and quantify flows (of material, energy etc.).
- ☐ Choose strategies for particular situations (construction of a building at a certain place) as well as for general purposes.
- ☐ Allow imagining of possible futures, by prospective techniques or by backcasting [ROBI89].

There is one idea which will have to be abandoned immediately: that there are "true" or "right" values of total energy needs, social costs, and pollution impacts. All answers will depend on the limits of the system and on the way the models work. This situation is rather new, and the main methodological consequence is that it is as important to say what models are used and where the system limits are as to present results. On the level of data management this means that the availability of different views of the same problem is not just an informative feature but is the central performance need.

A building is represented during its life time as the superposition of different flows and activities:

- ☐ Physical flows:
  - Material (building material, water).
  - Energy (embodied and operation energy).
  - Waste (building materials and waste from use).
  - Emission (part of waste released directly into the air or the water).
  - Information flows.
  - Financial flows.
- ☐ Basic activities imposed on the building:
  - Production of materials.
  - Construction.
  - Use.
  - Maintenance and refurbishment.
  - Demolition and disposal.

Money is an exchange medium that flows as a counter-current to materials, energy and information flows. Financial flows can therefore be associated with all of the physical flows and activities. This allows us to identify the internal as well as the external costs.

In order to be able to establish the life cycle costs, the flows of materials and the construction operations of a building must be known for its entire life cycle. This knowledge exists to a large extent today, but it is dispersed and in very different formats. All the flows and operations can be evaluated according to mass flow, energy flow, information flow, use of resources, financial flows and environmental impact criteria. It is very important to separate the quantitative data from the evaluation. The evaluation of the flows and their appreciation in a larger context must be possible from different points of view and in different ways. The goal of the evaluation is to allow the decision maker (designer, owner, politician, producer) to make conceptual, political, constructive, and economic choices.

Thus the development of a general hierarchical model for building applications has an immediate and a long term objective. The analysis of the different evaluation methods cannot be made on the level of these methods themselves (which method is "better" than the others?). Only their application to a certain number of known buildings will allow us to understand the difference between these methods. The aim of this analysis is the development of simplified methods which, in the long term, must be integrated into a general environment allowing the design team to make decisions by taking into account different points of view (form, function, costs, energy, structure, construction).

The presence of those other application views, though, with their common building domain and their often interdependent nature, raises issues of compatibility. Thus while directing our efforts toward a cost model, we must also follow a unified approach such as that of [BJOR92] accommodating the specialized viewpoints of architects, electricians, plumbers, and others working on a building over the course of its lifetime. Is it possible to include all of these interests within a single comprehensive model? If not, can we find a common conceptual foundation on which a variety of data models can eventually develop and intercommunicate?

Because of the difficulty of trying to anticipate every possible requirement of one all-embracing model, the second approach is probably more realistic. At the same time we must keep in mind the properties of the larger structures. The descending specialization from generic to individual applications, and thence to finer levels of detail, combined with the composite nature of many of the applications themselves, all agree with the common view of design as a hierarchical process and its results as hierarchies. The representative medium, then, should express building products as pyramids of encapsulated, reusable modules, with simple, flexible connections permitting the user a top-down or bottom-up approach to design.

2.0 Hierarchical Cost Estimation

Beginning from the perspective of our original application context, we seek to estimate the economic and environmental costs of construction, maintenance, and other operations over a building's lifetime [KOHL91b]. The model features an entity that can describe any procedure required during these phases: the production of an ingredient, assembly of a component, extraction of a resource, or provision of a service. As part of the search for a balance of mass and energy flows between the building activity and an external domain such as nature, a cost evaluation can be made by successive examination of the inputs and outputs of each process.

A building breaks down into the standard categories and subcategories of [CRB91], the further sub-elements of [IPBAU91], then the components, ingredients, and resources used to produce these parts. The simple example of the water-heated, two-room concrete house of *Figure 1* requires only a small subset of these categories. As decomposed in *Figure 2*, each item in the upper half of a node is the product of the aggregration or process in the lower half acting on a set of inputs below it, in turn products of earlier formulae in lower nodes, and so on down to the elementary materials and resources (or those considered so in the application domain). We use four of the CRB element groups {*A*-*Z*}: substructure *D*, superstructure *E*, mechanical and electrical systems *I*, finishing work *M*. Group *I*, for example, then contains the heating element *I2* implemented as a hot water system and further categorized into the IP-BAU sub-elements: boiler *I2.2*, pipe *I2.3*, radiator *I2.4*. The boiler is of steel, produced from iron, smelted from naturally occurring ore. Sub-trees can be shared, as here where similar concrete slabs are used for floor, walls, and roof. For clarity, the near-universal needs of energy and transport are shown here only in the shaded example of cement production. They, with labor, in fact contribute to most processes. Also omitted are the components for transport and dynamite and the use of water not just in mixing concrete but also in, say, metal and wood production. Each node's operation entails certain costs: economic costs in paying for required inputs, environmental costs in the consumption of natural resources and the generation of waste and pollution, and possible negative costs, of positive value, should the process generate useful byproducts. The aggregate entity associated with cement production might resemble the table of *Figure 3*, with descriptive attributes as well as collections of inputs and outputs.

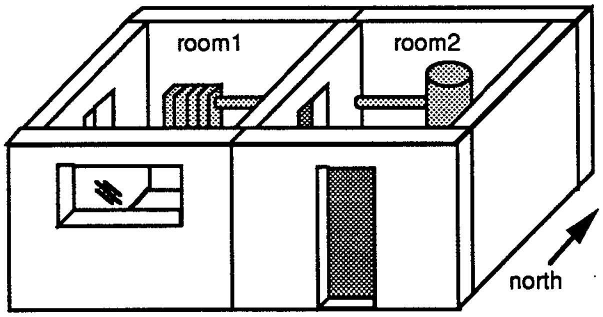

Figure 1: Two-room house example

Since the component trees of the building phases are of arbitrary complexity, they may be elaborated to connect to, or contain, what amount to entire sub-applications. The refurbishment of a building, for example, involves many tasks whose costs are influenced by the order in which they are performed and by the disturbance they cause for occupants. To optimize the former and minimize the latter, [GLAR92] analyses a model representing the space divisions of the building and the access routes between them. While this structure relates directly to issues of maintenance costs, it also contains elements (e.g., rooms) outside the range covered by the original cost evaluator. Only some of the components in the latter (e.g., walls and floors) will interest a refurbishment planner concerned largely with topological relationships not defined in the other model. An element common to both applications might use a different set of attributes for each configured into two or more networks. Thus our fundamental units must be versatile enough for such specializations while providing also for any necessary overall structure.

3.0 Approach

3.1 STEP/GARM Constructors

Among previous work to support different viewpoints on a common or connected database [VANN91, WILL91] it is difficult to find something general enough to adapt to our purposes while specific enough to be useful. The object frames of [AMOR91] use multiply-valued slots to describe alternative versions or *worlds* within a single system. This concept is adaptable to our multiple applications, but must we separate views at such a low level? We need not just alternative versions of individual attributes, but a way to divide sets of attributes while also assembling these separate data structures according to some common format or constraints. The arrangement of these attribute sets, or aspects, is discussed later.

The multi-layered, multi-connected entities of our desired model recall a familiar concept [e.g., BATO85] of sub-component assemblies encapsulated as *implementations* of well-defined *interfaces* allowing top-down or bottom-up design, problem subdivision, and alternative solutions. This device, introduced as a GARM standard in [WILL88] and elaborated in an earlier description of our approach [BEDE92], models a single product or sub-product from both functional and technical viewpoints.

Thus in *Figure 4* components appear as *Functional Units* (*aFU1*, *aFU2*, *aFU3*, *cFU1*) connected laterally through *Ends*. Of these *aFU2* and *aFU3* form a subassembly or *Technical Solution* (*TS1*) which, ignorant of their internal connections, derives their unconnected Ends as *Ports*. *TS1* joins to the complex *cFU1* with corresponding Ends which then connects to an End of *aFU1* at the higher level. Revisions or alternatives are introduced as different TSs implementing *cFU1*. There is no fundamental difference between atomic and complex FUs, simply one of state: the design of *aFU1*, say, has not advanced to a stage requiring a TS and may never need one. Specialized FUs, though, may define an inherent distinction.

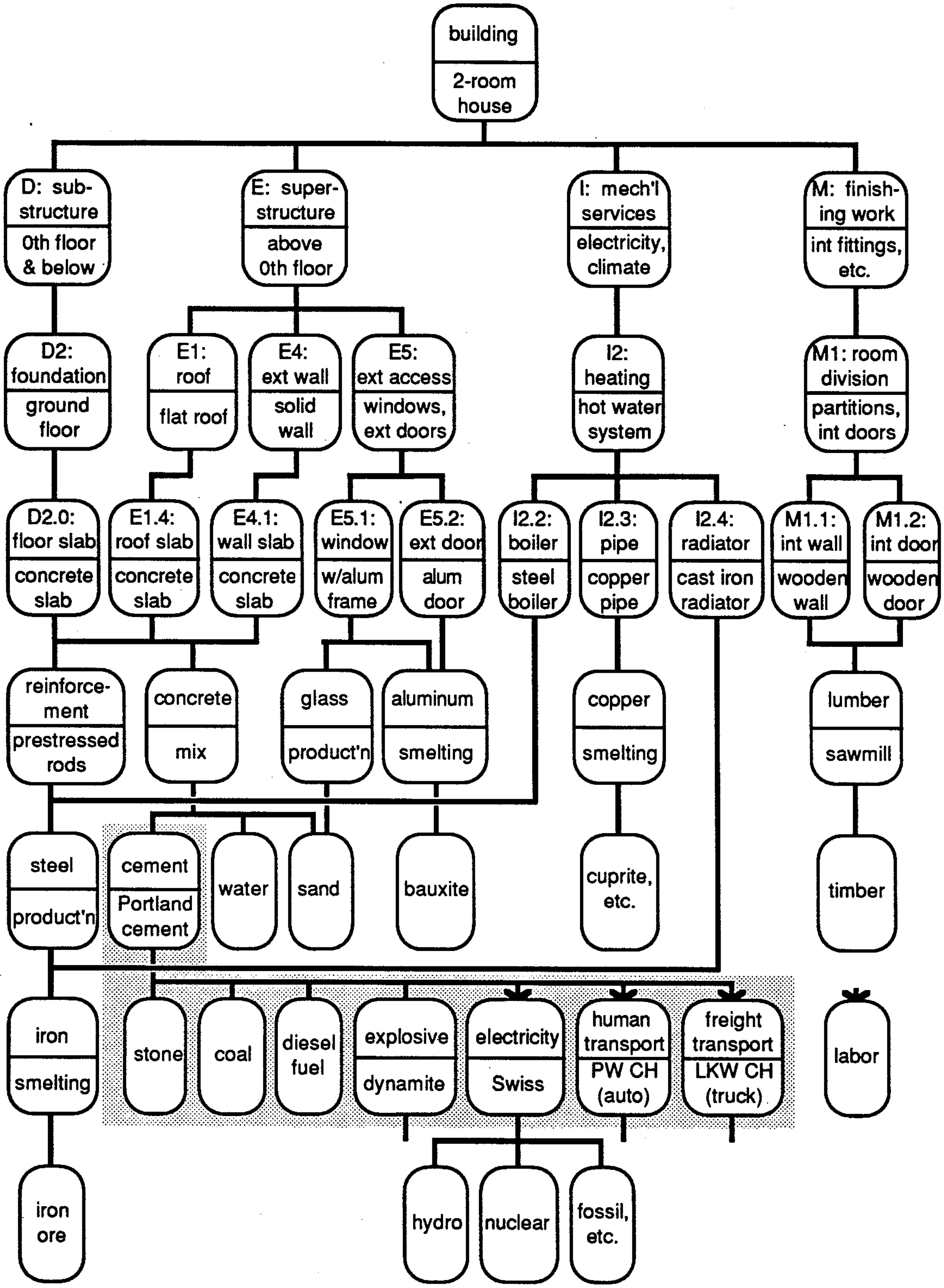

Figure 2: Modeling building costs using process entities

Attribute	Value
Name	Cement
Description	Portland cement
Producer	Zement AG
Package size	50 kilogram sack
Code for composition	SIA Norm 215
Code for permitted uses	SIA Norm 215
Code for restricted uses	SIA Norm 215
Proposed disposal	inert
% actually recycled	impossible
Date of information	8/8/88
Source	3
1 = literature	---
2 = calculated	---
3 = measured	---
Level of detail	2
1 = crude	---
2 = medium	---
3 = fine	---

Attribute	Value
Units	1 kilogram
Inputs	---
goods and services	limestone/marl (1.5 kg)
	coal (0.12 g)
	diesel fuel (0.05 kg)
	explosive (0.1 g)
energy from network	electricity (0.1 kWh)
human transport (auto)	PW CH (0.5 Pkm)
freight transport (truck)	LKW CH (0.005 tkm)
Outputs	---
emissions	---
air	dust (0.001 kg)
water	none
waste	filter dust (0.01 kg)
category	special waste
method of disposal	Code 2021 (VVS)
	treatment .04
byproducts	none

Figure 3: Aggregate cost for cement production

The Ports of a TS always derive those Ends of its subFUs unconnected at the lower level, encapsulating those components so that only their external, higher-level connections need be known to the outside world. Splitting the FU and TS into separate entities encourages this encapsulation and allows the substitution of alternative solutions without affecting the rest of the structure. Conversely, a given TS sub-tree can be reused any number of times within a structure by attaching it to several different FUs having similar specifications. Such a connection is uncomplicated because the only other vertical links to account for are those between the Ends and Ports of the same FU/TS pair, and all lateral links are internal to the TS. Any interaction involving, say, the left End of *aFU2* will actually ascend through the deriving Port, up to the left End of *cFU1*, across to the right End of *aFU1*, and, were *aFU1* complex, down from there. Here no further descent occurs. Like TSs, an FU can also be reused but as a component shared by different assemblies, exhibiting identical simultaneous behavior in each (the case, say, of a wall between two adjoining rooms).

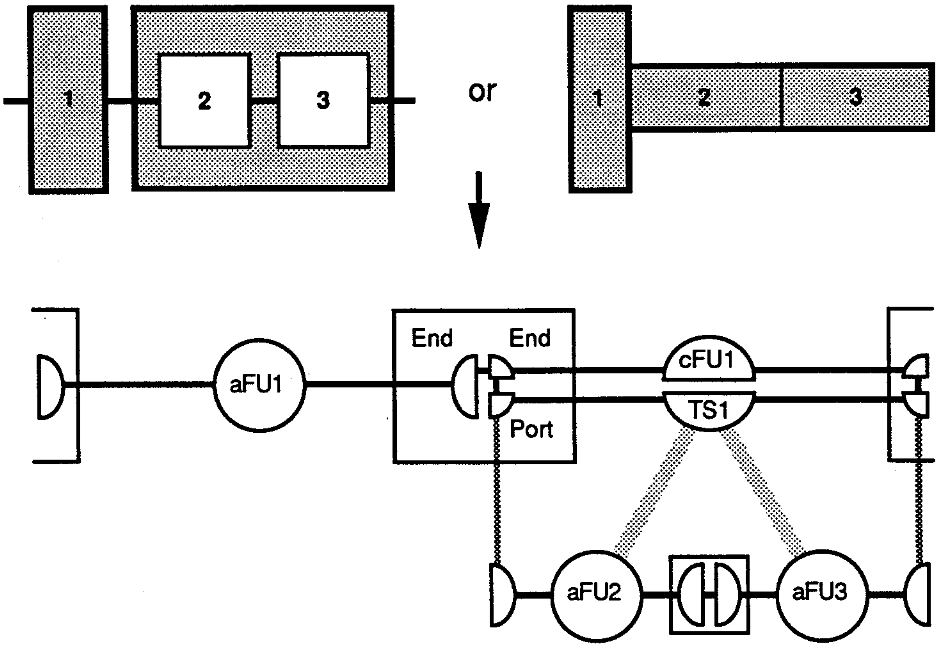

Figure 4: Sub-component assemblies modeled according to GARM

3.2 Topological Issues

[WILL88] sets out in detail a "meta-topology" of bounded domains that provides a foundation for GARM but no explicit vocabulary of basic configurations. The FU/TS structure exemplified above accounts only for structures whose sub-components at any given level are connected in series; each juncture involves ultimately just two atomic units. Topologically this corresponds to a pair of domains or objects (*1* and *2-3* above) whose internal decomposition, not affecting the joint connecting them, is of concern within but not between those objects.

One common situation in practice is that of sub-components joined in parallel, with each maintaining a direct connection to the same external entity (as with sub-objects *2* and *3* to object *1* in *Figure 5*). Such a multiple juncture of Ends is easily represented since in GARM each Port can derive more than one End just as a TS can decompose into more than one sub-component. Thus the Ends of *AF* and *aFU3* find a common external connection in their derivation by *TS1*'s left-hand Port. A vertical line joining these two Ends conveys this status visually.

Some structures are not directly configurable using serial and parallel subassemblies but require extra joints and decomposition levels leaving little conceptual resemblance to the original subjects. In *Figure 6*, for example, the high-level connection between subassemblies *1-2* and *3-4* conceals underlying sub-links between FUs *1* and *3*, *2* and *3*, *2* and *4* rather than a common joint at which all sub-units meet. To more gracefully represent this situation in GARM we can use multiply-deriving Ports but must preserve the separate connections between pairs of Ends at the lower level. A new type *MultiPort* serves for all such cases describable only in terms of sub-connections between separate TS assemblies.

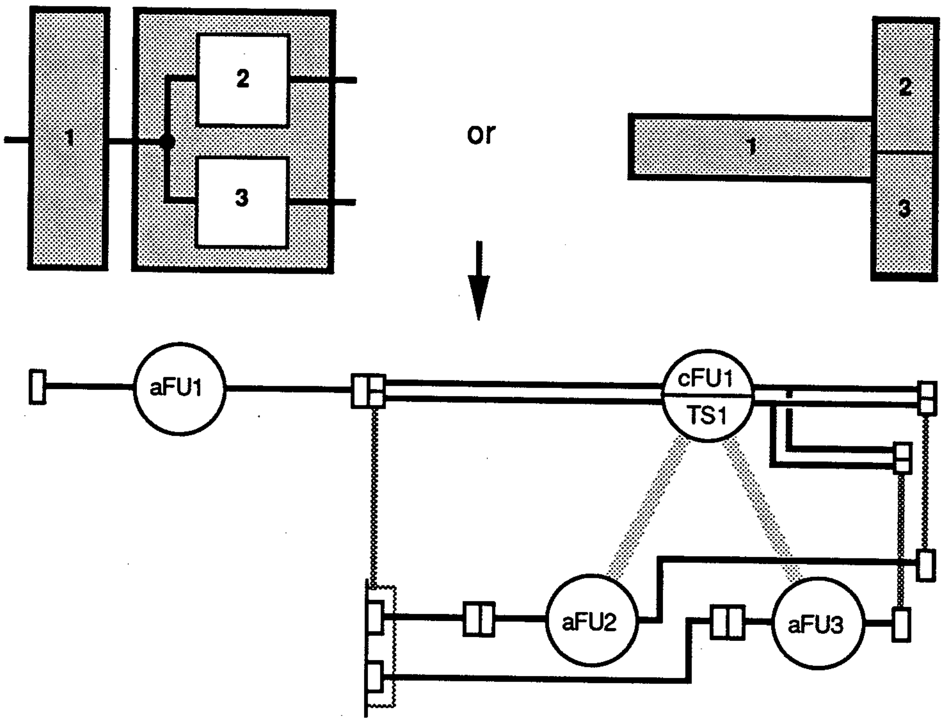

Figure 5: Modeling an assembly with parallel sub-components

3.3 Formal Constraint of Object Relationships

FU and TS relationships as defined in [WILL88] easily convert to the NIAM notation [NIJS89] of *Figure 7* to clarify interactions among object types and the constraints that control their assembly. An FU, component of several TSs, can in turn use several alternative TSs; its Ends several corresponding Port sets. Each TS can implement several FUs while comprising several sub-FUs; its Ports several corresponding End sets while deriving several sub-Ends each. A TS may have several Ports, while each FU may have several Ends. Finally, within a given TS, each End may mate with Ends in a connection internal to its level, preventing either End from being derived by a Port of the TS containing it, since as described in Section 3.1 only unmated Ends devolve to higher Ports. The diagram here is for the general GARM level; applications will use specialized subclasses and more restrictive relationships.

4.0 Representing the cost model in GARM

The GARM format must be easily adaptable to applications such as those already described. To represent building costs, sand, labor, and the other basic resources of *Figure 2* become atomic FUs, while each category (superstructure) or product (concrete) becomes an FU/TS pair. In the latter, a complex FU represents the specification in the upper half *of each divided box and a TS its categorization or implementation process in the lower half. Figure 8* shows the structure for the cement production sub-tree. This TS has seven FU sub-components, with four, an explosive, electricity, and human and freight transport, considered manufactured products heading their own submerse. Flanking the seven ingredients are their Ends derived by common Ports of the Portland cement TS, uniting them as parallel siblings.

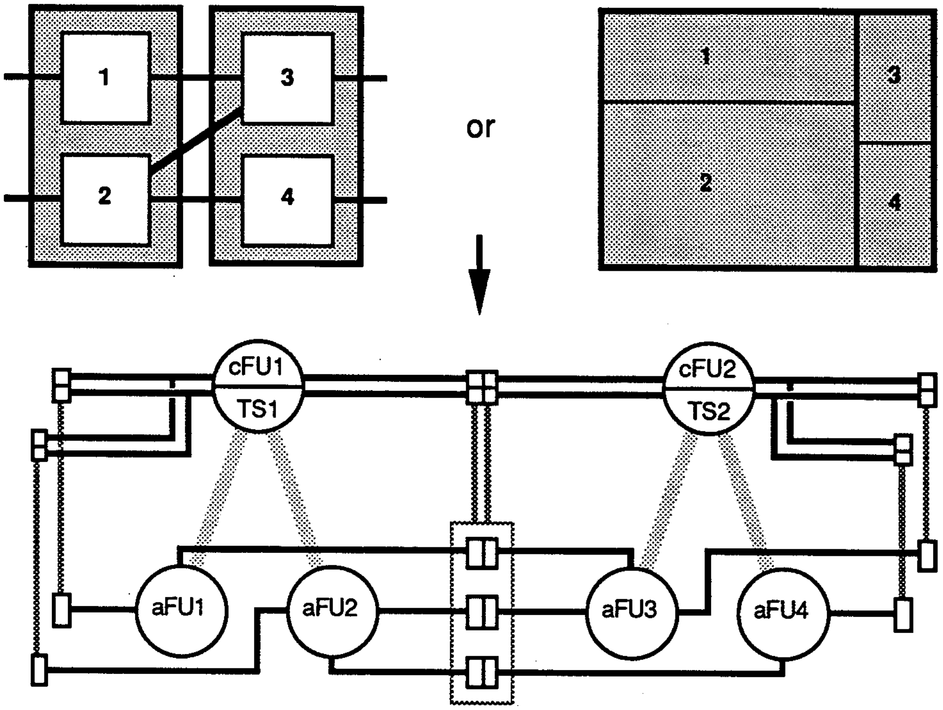

Figure 6: Modeling components with complex connections.

Production costs of each component FU in money, waste, emissions, and byproducts are requested through its left-hand End and returned through the right. When a TS sub-tree (Portland cement) receives a request for evaluation from one of the FUs it implements (cement), it propagates the request through its left-hand Port down to its sub-FUs. Each receives the request from its left-hand End, finds its own cost (if atomic) or evaluates its TS (if complex), then sends the result out through its right-hand End. These subtotals accumulate in the right-hand Port of the first TS, which returns the total to the requesting FU. This evaluation descends recursively as deeply as required to traverse the sub-tree. Any TS reused by different FUs will be queried repeatedly; for these subsequent occasions, however, it simply retrieves the preserved result of the first evaluation without re-traversing its sub-tree.

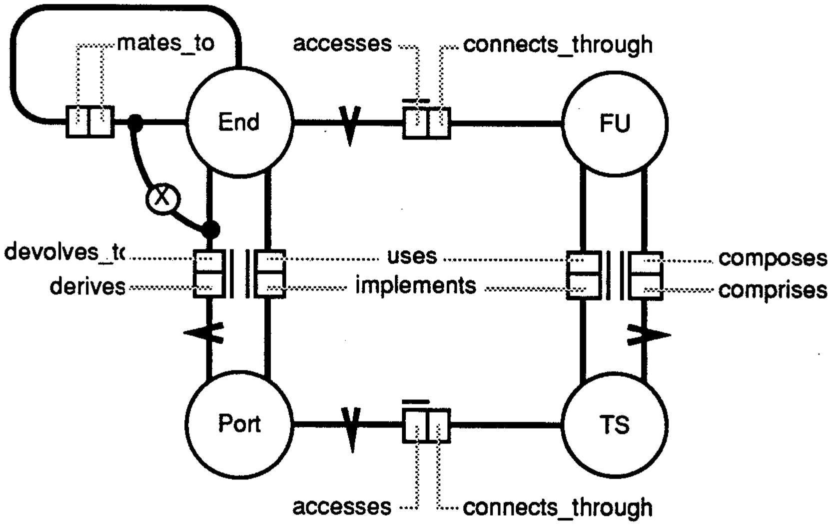

Figure 7: FU/TS relationships represented in NIAM

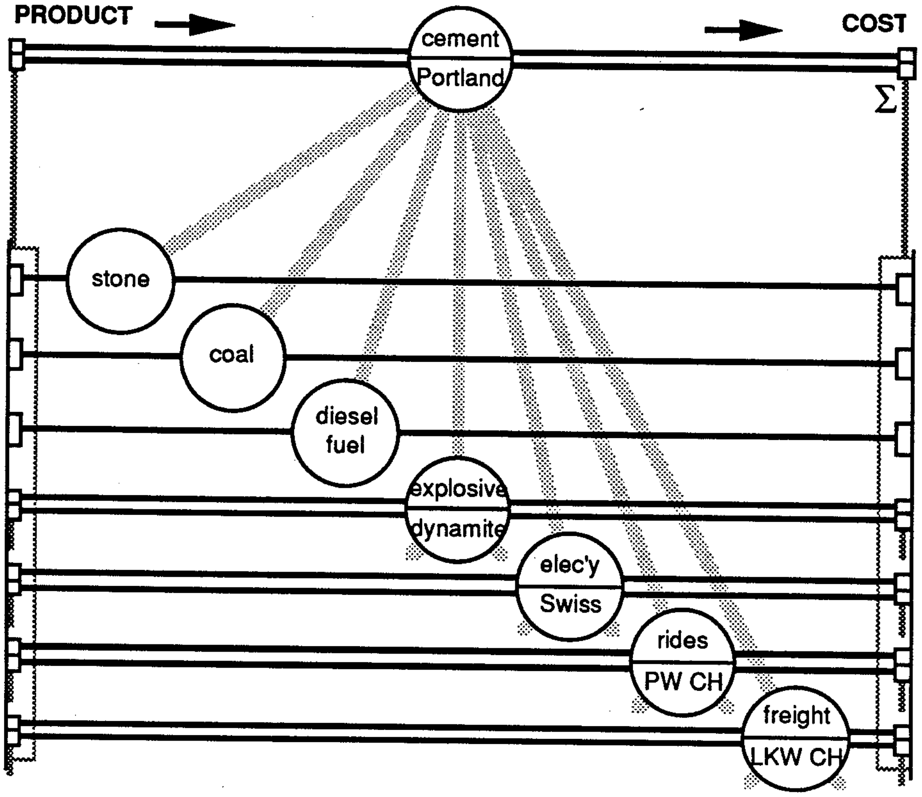

Figure 8: GARM representation for cement production

Representation of costs for life cycle phases other than construction differs little from the above approach. Where appropriate, the FU at a particular node possesses alternative TSs, each at the top of a sub-tree representing costs for the corresponding phase. This branching occurs chiefly at the fourth (IP-BAU component) level of *Figure 2's* building tree, since nodes above this define categories independent of phase, and those below ingredients and resources that would usually be new whether used for construction or maintenance. A cracked concrete wall, for example, would be patched with new concrete. A sub-tree for demolition costs would contain non-material ingredients such as labor and transport to dismantle and/or remove a component, along with such destructive materials as paint remover or dynamite. Certain phases of a node may use more than one of these alternative TS sub-tree; thus replacing windows during refurbishment would require the removal of the old windows followed by the installation of new ones. A component node would contain evaluation methods for each phase that would know which TS or combination of TSs to invoke.

5.0 Unifying disparate views

5.1 A Collective Data Model

Having modeled separate applications with GARM's FU/TS units, can one connect them into a single coherent framework? Each object existing across various applications should be able to display hierarchically arranged viewpoints, avoiding both the disorder of piling all information into one heaping object and the redundancy resulting if complete and separate views were simply lined up side by side. The separate sub-categories or *aspects* for a given object would thus appear in one or more layers beneath the unit defining the object's generic identity. An additional bottom-most layer would allow an object to assume, within a single application, multiple *roles* with different behaviors (as opposed to a shared FU performing identically in more than one place).

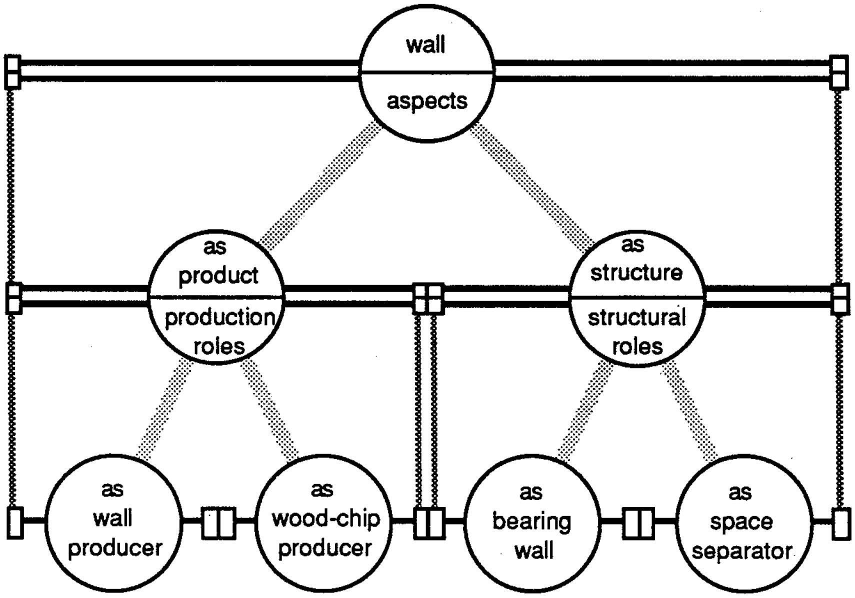

Figure 9: GARM representation for different aspects and applications

The resulting structure can be represented, as in *Figure 9*, as a hierarchy of FUs apart from the main composition tree. Here, a single instance of a wall would have separate aspects for cost and, say, refurbishment models, each holding information relevant to its application. Within a single decomposition, however, this wall might have to appear twice. Thus if a bearing wall of a building traverses an apartment, that section of the wall must serve both as a separator in the apartment's interior space (shared by two rooms) and as a component of the building's structural framework. The wall's production aspect in the cost model might require multiple roles as a way to represent byproducts: the same process that manufactures a wooden wall might also yield, at no additional expense, a quantity of wood chips suitable for insulation or in particle board used elsewhere in the cost hierarchy. Potential lateral connections shown here might express semantic relationships between different aspects and roles, preventing, for example, the movement during apartment refurbishing of a partition wall that also has a structural role.

Thus each FU is intersected, as in *Figure 10,* by the three mutually perpendicular planes of the hierarchies in which it participates. The object serves as 1) a component in a given application's decomposition, here a separator within an apartment plan, which 2) may be only one of several roles assumed across one or more applications by different aspects of a single wall entity, and which 3) is also an instance of the wall subclass of, say, a barrier superclass. The first two of these are represented in FU-TS form as already described; for the third the class mechanism of the implementing object-oriented environment (currently C++) should suffice. Since in this approach objects themselves and their fragments (aspects and roles) are all full-fledged FUs, development can proceed from general to application-specific terms or by combining separately implemented units.

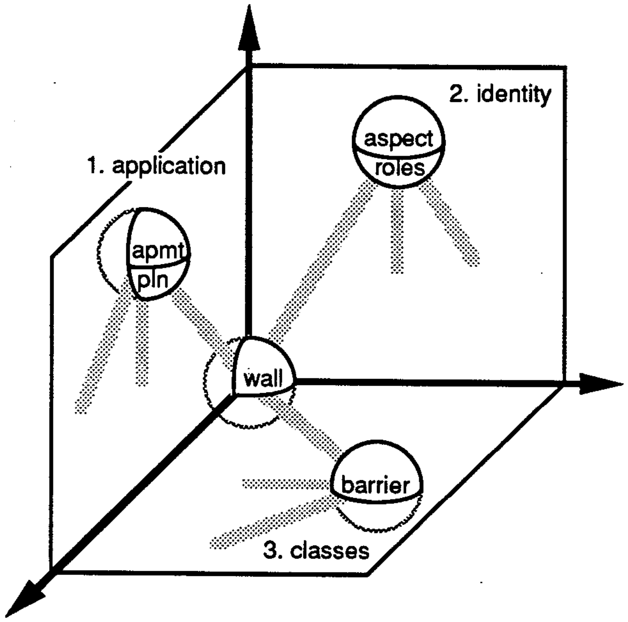

Figure 10: Intersection of three orthogonal hierarchies

5.2 Class Extension

The GARM structures discussed here are built from entities defined as generalized object classes and their instances. These classes suffice for the formation of these structures, but to embody their functionality within applications they must be extended to specialized subclasses. The GARM class hierarchy appears in *Figure 11* from its root down through the cost model. The *Co-Object* base class defines the mechanism for the autonomous activity pursued by each object; below this are subclasses allowing construction of an application-independent GARM framework. *Nodes* form components and *Connectors* join them; at the next level these become the familiar FUs and TSs, Ends and Ports. FUs acting also as *Aspects* and *Roles* allow formation of the above mentioned identity hierarchy without fixing objects at particular levels. Thus if an object has only one Role to play in an application, that Role's FU can bypass the needless level of multiple identity and serve directly as that object's one Aspect within the application, or as the object itself if it has no other Aspects.

The application-independent GARM classes contain the attributes and functionality to represent component hierarchies and the binary relationships of *Figure 7's* NIAM graph; they also enforce restrictions ensuring necessary arities and class compatibilities and preventing improper constructions. Thus Ports and Ends are created only through existing TSs and FUs and never as independent entities, two Ends connect only if their FUs are components of the same TS, and no TS can contain itself in its sub-tree.

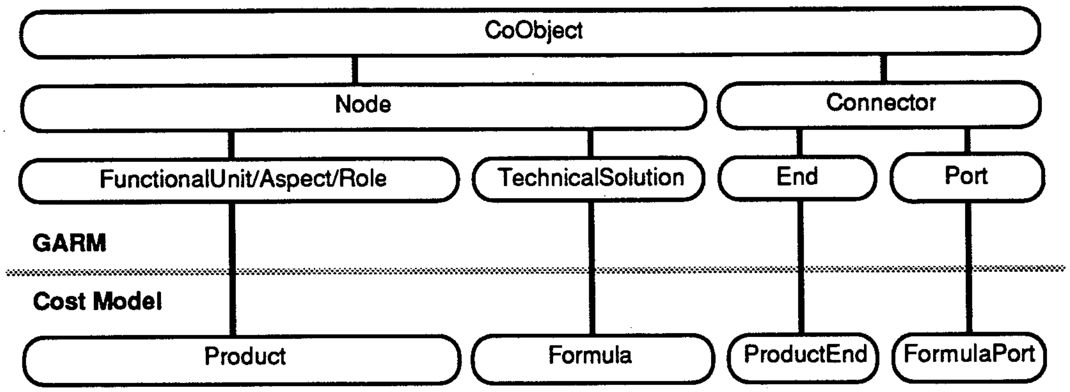

Figure 11: Hierarchy of general and specialized classes for building cost model

Descending to the level of classes peculiar to the cost application, every purchasable item, substance, or service, whether basic or manufactured, is in the *Product* subclass of FU which provides attributes relevant to cost but independent of a particular solution. These include a name and description, a unit of measurement, and the quantity, peculiar to each instance, used as an ingredient by the parent TS to produce one unit of the latter's product. If atomic the Product will also refer to an aggregate unit cost, which for a composite Product is calculated from its TSs as already described in *Section 4*. This latter summation process, which totals the costs of sub-components and adds a (usually environmental) cost inherent to the solution, is defined in the subclasses *Formula*, *Product-End*, and *Formula-Port*. The entire class hierarchy is intended to be directly transportable to an object-oriented language such as C++, in which a simple version of the cost evaluator has been implemented.

5.3 Maintaining Integrity

Once different applications establish common interests and begin to share data they will in most cases require a mechanism to preserve the integrity of their unified structure. When in a CAD tool, for example, the user changes the layout of a room, this will alter the sizes of its floor and walls, which will in turn alter the amount of materials required for that part of the building. This, of course, affects any subsequent evaluation of construction and maintenance costs. Interrelated data, then, must be joined by a set of constraints as discussed briefly by Björk as a factor in unification, and as proposed above in connecting Ends and Ports between Aspects and Roles. [MACK92] suggests one way to lend a structure to the design process itself by treating that entire process as a continuous attempt to satisfy sets of constraints.

Each stage of the design is associated with such a set and cannot be completed without satisfying its conditions. One stage may include as a prerequisite the successful completion of a previous stage, which may itself depend on a still earlier stage, thus enforcing a linear order among the design tasks. Alternatively, a stage may depend on several otherwise independent stages which can be developed simultaneously or in any order desired. This structure of constraints is easily adapted to the GARM format, with each design stage as an FU implemented by one or more TSs, each decomposing into a set of previous stages connected in series or parallel. A stage associated with a specific component can be represented as a design Role of that entity within its application or as a separate Aspect in an overall design tool application.

6.0 Conclusions

The framework described here promises to assist in orderly and consistent development of a number of related applications in building design. This development has proceeded as far as a set of working GARM subclasses for simple building cost evaluation, as well as a topological model for refurbishment now being implemented. The next major step towards realization of the ideas discussed here will be the construction of a database of process objects to represent the costs of transforming basic materials and resources into ingredients for the manufacture of components. This will contain data, gathered from industry, reflecting the building cost hierarchy of *Figure 2* from its lowest levels up to but not including the IP-BAU level. Aspects, roles, and related constraint organization must be dealt with in more depth to effect firmer and more useful relationships between applications. Refinement of object definitions must continue. For now, the GARM model as applied here appears to be a comprehensive and flexible foundation on which to base future development.

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PART TWO: WORKSHOP SESSIONS

During this section of the meeting participants addressed three critical research questions associated with the life-cycle analysis of buildings:

- ☐ Acquisition of data
- ☐ Structuring of data
- ☐ Evaluation methods

Position papers prepared by Sebastian Moffatt of *Sheltair Scientific Ltd.*, Vancouver, Canada were used as the framework for discussion.

SESSION ONE: ACQUISITION OF DATA

POSITION PAPER:

1. Introduction

Issues related to data acquisition have been organized into five key questions:

Issue 1:	*What are the preferred data sources?*
Issue 2:	*How should the data be qualified?*
Issue 3:	*What can be done to facilitate data sharing?*
Issue 4:	*What are the design features of an effective data collection system?*
Issue 5:	*What are the priorities for collecting data in the near future?*

Issue 1: What are the preferred data sources?

Generalizations about data preferences are difficult to make without first establishing criteria for judging all of the data. For example:

Reliability:	Is it based on empirical measurements? Has the primary data been verified by credible sources? Are there cross checks or other methods validating the range and order of magnitude?
Detail:	Is the data sufficiently precise to permit useful interpretations?
Specificity:	Is the sample large enough to allow for statistical manipulation?
Completeness:	Are gaps in the data a problem? Are the units acceptable? Are important variables kept distinct?
Age:	Is the data current enough to reflect the pace of regulations and technological change?

In reviewing these criteria, some specific questions need to be answered:

- ☐ *When is poor data worse than no data?* Caution is required when using data that is unreliable, or too general, or too old, etc., because of the potential for misleading the user groups. It may be worth outlining those areas where special care is warranted.

  For example: The variation in emission control efficiency can be great, and makes it difficult to use existing data without making grand assumptions. This is true especially for imported product from some developing countries where regulations may be inadequately enforced. Even in Europe and N. America, where strict regulations are in force, obtaining reliable data on post-control air emissions can be a problem. Much of the data collected on air emission factors by industry is based on uncontrolled emissions per tonne of product. It is difficult to know the usual operating effectiveness of emission control technologies, or even what kind of technology is in use. Particulate control technology varies greatly in efficiency, and a `default' value can be misleading. In the case of SO_2 reduction, control technology is a moving target, driven by legislation for controlling acidic precipitation.

- ☐ *Are averages across an industry of any real value?* Gross averages are a problem when trying to optimize design of a building. Too often the variations from plant to plant exceed the differences between one type of material, and the alternatives. Using a gross average can unintentionally tar good plants or good technologies with the poor performance of the larger industrial sector of which they are part. Promising new products get obscured by the statistics, and the opportunity for quickly rewarding technological innovation is lost. Given this problem, is there any value in rating building materials and buildings until environmental specifications exist for all of the materials in the marketplace?

☐ *In the long-term, what are the preferred sources of data?* What is the ideal combination of data sources, to minimize drawbacks, and allow for appropriate checks and balances?

Table 1 An overview of the Data Sources

Analysis	General Sources	Benefits	Drawbacks
Input-Output An I-O table is a square matrix that summarizes the commodities needed to make other conditions in monetary value. Using the I-O table analysis it becomes possible to calculate the energy requirements of a specific industrial sector directly from their purchases from the energy sector, and indirectly from the energy purchases of their suppliers.	Government Statistics, usually based on data collected by industry	- captures all the indirect energy resources - fairly robust and cross-checked - in some countries the I-O data has been corrected to account for own-product use and self-generated power, and to separate energy by type	Methods vary Very Imprecise data Usually out-dated by 5 years + Aggregation of diverse industry types as products with dissimilar energy intensities Monetary units need to be converted to physical units Physical quantities sometimes are kept confidential Different energy resources are lumped together
Process Analysis A source of theoretical data, usually based on energy thermodynamic analysis of the engineering processes involved in production of materials, or maintenance of final products. This data may include energy balance and mass balance calculations.	Industry analysts (including academics and professionals working for industry association, labs, and larger corporations)	generally available easy to update well documented	Inputs are often confidential Inputs to process can't be separated from company totals variations occur from producer to producer and year to year marginal energy can vary if industry operates much below 100% capacity tricky to partition the process inputs to each company product
Primary Data Base Plant surveys, case studies, questionnaires and other vehicles used to collect data on each sector and region.	Researchers & Industry Associations: (including manufacturers, installers, suppliers, service companies, as well as the associated resource industries and utilities	precise and potentially very accurate current easily verified in cases of dispute	data is very specific to plant location, age and size sample size usually too small to be statistically significant high data collection costs for companies that participate.

Issue 2: How to Qualify the data

Ideally all data would be qualified with confidence limits which reflect variations in the data, and the potential range of error in the methods and instruments used to collect the data. At present the data sources are too crude to permit such statistical methods. The margin for error must be largely implied by other characteristics, such as how the data was collected, its age, etc.. Some type of information will need to be included with the data, as qualifiers.

- ☐ What are the qualifiers that should accompany all the data? - Date; Current reference; Primary source; Measurement technique, or type of analysis; Mean and Deviation, or Best/worst values
- ☐ Doesn't each industry require a coding system, reflecting the range of differences in sources and measurement techniques?
- ☐ How can all of this data be accessed as the data is aggregated and combined?
- ☐ Should a point score be used to indicate a degree of reliability?

When the results are based on multiplying two factors with low reliability, little confidence can be placed in the result. How can the degree of reliability be easily communicated to potential user groups, to avoid anyone trusting data too far? One approach has been to develop a scoring system for use with all the data. These kinds of systems work best if the scoring method is well defined, and simple to use and understand. Is it possible to agree on a standard approach to scoring? Is there an approach used elsewhere that may be appropriate? Who would be capable of defining a scoring system? Is it a good idea to use a numeric system? - Scores from 0 to 10, for example, are sometimes desirable because they easily convert to accumulated weighting values, or percentages.

What can be done to accommodate highly diverse data sets? How can data be qualified when the variations are extreme? For example, air emissions from coal-fired generating plants can vary significantly, depending on the type of coal used, and the technology. (Nitrous oxide emission factors vary more by type of coal than fuel type.) Is it reasonable to use best case and worst case values in such conditions?

Should data on emissions be qualified according to the environmental and legal context? Simply adding up the emissions from each process or stage in the life of a product can be very misleading. Often the emissions are of importance only if they exceed the carrying capacity of the local air and water sheds, or if they are not already regulated and controlled in ways that reflect their true social costs. Is it feasible to qualify inputs and outputs according to location?

Issue 3: What are the design features of an effective data collection system?

Data collection is a task that needs to be coordinated. The responsibility is shared amongst numerous players (see figure below). Where does co-ordination come from? What is the division of responsibilities? Lutzkendorf has pointed out the problems in the field of energy analysis, where no central group undertook to set limits and standards, to manage and update information. He has proposed a division of responsibilities:

- ☐ Corporations to keep track of embodied emissions, energy and waste as a product is acquired and sold, (with the transportation costs allocated to the purchaser).
- ☐ Industry associations to collect and organize the product specific data.
- ☐ Researchers (government departments, or academic institutes), to collect data at the national or continent wide level in the broader areas of:
  - transportation of goods (rail, air, sea, road);
  - energy (mix of sources and emissions);
  - scenarios (for renovation & demolition).

Is the role proposed for industry associations something they can afford and manage? Are some associations unlikely to cope?

How can researchers obtain cooperation from larger corporations that are not normally influenced by competitive forces?

Are plant level questionnaires becoming too onerous for industry to accept?

Could an aggressive campaign to acquire data in the short term produce an obstinate or unfriendly response from industry in the longer term?

How will the traditional industry sectors cope with the complicated task of adapting their data base to reflect rapid changes in technology and regulations?

Is there a new role for National Statistics agencies? Can these groups be encouraged to meet and address the needs of researchers in this area?

Can the national reporting by industry require the inclusion of data on emissions and uncontrolled wastes?

Could a change in emphasis from new buildings to existing buildings place additional responsibilities on the occupants of buildings, and on the labour intensive renovation/service industry?

Issue #4: What can be done to facilitate data sharing?

In an area where the quantity and variety of data requirements is so over-whelming, the sharing of data is the solution to an otherwise impossible task. Data needs to be shared between the many different segments of the industry, as well as between research and monitoring agencies within countries, and worldwide.

Are similar formats and parameters important, and if so, what is most appropriate? Should environment related data be standardized in the method of reporting as are groups of data on the products (e.g., workplace safety data sheets, standards certification labels, import/export forms,). And if so, what is the minimum information required on any material or service? (Refer to the format presented by Lutzkendorf, and *Table 2*).

Do we need a reference guide for converting from 'industry' units to other physical units? Most researchers are required to standardize units in order to complete life cycle costing of buildings. In addition to requiring lots of time, the conversions from industry units (sheets, items, area, length, hours, litres, etc.) to physical units sometimes involves a choice of procedures and assumptions. This can lead to problems when sharing the data with others who may have different assumptions. For example:

- ☐ What is the mass of a nail, brick, stud, window etc.
- ☐ How much diesel fuel is required to move a m^3 of earth?
- ☐ When the volume of lumber shipments are recorded by the transport industry, are the dimensions based on nominal or finished sizes of lumber?
- ☐ Do the quantities of materials used in assembly of a product (or building) include an increment for typical waste due to damage, loss, and human error?

How can industry be encouraged to use units appropriate for calculating average impact per unit of product? For example, at present the out-fall emissions from pulp and paper, mining and smelting and some other industries cannot easily be averaged. Although process studies provide summary data on water emissions, the ratios are inappropriate: volume of discharge containing suspended solids per hour, or volume of discharge per paper machine.

What is the obligation of researchers to respect concerns over confidentiality of data? At present, confidentiality can be a problem in two areas: sales quantities, and inputs to a process. Statisticians are usually willing to respect every request for confidentiality, since they can always aggregate and average the data at greater levels. However the public has a right to effective environmental evaluation and design, and may need to know which supplier's materials and services are most appropriate from this perspective; even other manufacturers will frequently have a need for precise information on the inherited environmental impacts. How are these sometimes conflicting demands resolved? Can requests for confidentiality be judged by an impartial group? Is it practical for researchers to offer industry a chance to peruse the more sensitive data prior to publishing?

Is there a need to consider the implications of data requests on the poorer nations, and the smaller business? Where groups lack the skills or financial resources to undertake data collection and evaluation, is it necessary to propose alternatives?

Table 2: An overview of the data requirements

CATEGORY	BASIC DATA SET	OPTIONS
Building Materials	☐ All standard resource inputs and output related to production of a building material and auxiliary processes. ☐ Cross references to other data sets, (economic cost, specification, technical functions, etc.)	☐ Life time off-gassing ☐ Workplace hazards ☐ Noise ☐ Radiation ☐ Scarce resources ☐ Hazardous resources ☐ Location of emissions
Building Performance	☐ Direct operating energy (lighting, heating, cooling, motors) ☐ Expected lifetimes and replacement percentages for each unit or assembly	☐ Ventilation effectiveness ☐ Recycling potential ☐ Retrofit upgrade potential ☐ Community resource requirements

Issue #5: What are the priorities for data collection?

Some big gaps are being encountered when researchers attempt to obtain an overall assessment of resource inputs and emissions for buildings. These gaps occur because data is either missing, or of very poor quality. Some of the gaps or `deficiencies' already identified have been listed in the first column of *Table 3*. The Table has identified a number of criteria that can be used to help in rating the relative priority of the data collection tasks. Information is of special urgency when one or more of these criteria are suspected to apply. Can we expand and prioritize this list of data deficiencies?

Table 3: Evaluating the Data Collection Priorities

	CRITERIA FOR JUDGING PRIORITIES					
Data Collection deficiencies	Significant Resource Inputs	Especially hazardous Emissions	Large Quantities of Greenhouse Gas	High Variability of data	Economical Alternatives Exist	Environmental Regulation Pending
Transportation of Materials	X		X			
Paints and related products	X	X				X
Off-gassing of interior finishes		X			X	X
Installation services and activities	X			X		
Lifetimes of materials and assemblies	X			X		
Foam Insulation		X		X	X	X
Others?						

Table 4 Basic Data for Establishing Resource Impact of a Building Material

Units of Material

Embodied Energy	Emissions			Environmental Impacts
	Air	Water	Land	
Oil	CO	Organics	Calcium	Agricultural Capacity
Coal	CO2	Suspended	Mercury	Persistent Hazards
Nuclear	SO2	Oils	Lead	Scarce, Non-renewables
Hydro	NOx	Chlorides	Nickel	Loss of Habitat
Natural Gas	CFC	Iron	Nuclear	
Biomass	CH4	Mercury	Solid/Inert	
	Particles	Cyanide		
	Ammonia	Heat (?T)		
	Lead			
	Zinc			
	Calcium			

ISSUES RAISED IN WORKSHOP DISCUSSIONS:

What is truly possible?

☐ Is a model is possible? or relevant? Does a model offer a useful design tool? Is data ever likely to be adequate for use in models for use by designers?

Should data collection reflect the importance of calculating externality costs?

☐ Need to collect data today not just on emissions, but also data that gives a sense of costs; i.e., acquisition of data that is based on externality costs. Suggestion that if you're even marginally successful in introducing externality costs, let the accounting dollar be the indicator by which preferred choice / decision is indicated. This provides a common basis for decision-making which creates a parallel between those looking for return on investment and those interested in environmental impact. Question is whether this would provide a practical approach which would render obsolete all other approaches.

☐ But is it possible to internalize all the costs? For example, documentation of human health costs is sometimes key to decision-making, and yet is difficult to gauge.

☐ No matter which approach is adopted, however, you still to go through process of collecting data and allocating resources back to where they were produced.

What is the minimum standard for quality of data?

☐ It is not always a question of preferred source; you have to take what is available.

☐ The point was made that poor data is worse than not having data, as generalized factors can mislead people. A lot of discussion ensued over the value of averages. Do averages tend to obscure? Do they provide too crude a tool for measurement? Deviations are very large even within same materials.

Concerns over the participation of manufacturers and the use of Process Data in place of Input/Output data

☐ Question of whether you can trust the manufacturers to provide reliable, unbiased data? Most people don't. Where is reliable data found then?

☐ Question of validity of process-based model versus input/output model. Which system provides a more reliable, comprehensive source of data?

☐ Depending on process-based data may mean that you miss half of the data. Central processes of production are very hard to average. Given this, is the ideal a revised input/output model? Would this represent the preferred method?

☐ Another possibility is to conduct engineering analyses rather than relying on data from the producers. The tendency is to use a number of alternative prediction techniques to plug into models based on engineering analyses. If this can be supplemented with data form the producers, great, but if you have to depend solely on producers, data is less reliable.

☐ However, the input/output model only starts to function once you go beyond the central processes; it is not a substitute for the process model. It gives information that does not always evolve from a process analysis. It always goes to average values, which represent the best approximation, but which are useless for the process steps. Great variability exists in the way that different manufacturers make the same product; it's very difficult to make a comparison. Also, one manufacturer is making more than one product at any given time, albeit from the same material.

☐ View that the only people capable of providing data over the long term are the producers. This is a given. The important questions then become how to convince the producers to collect the data and provide it, and how do you evaluate it? What producers know is what comes in (what they buy) and what goes out (products and wastes), as well as how things are allocated once they come in. We don't want to know how they actually produce things, we are interested in emissions and wastes. We must apply pressure; we must ask for reasonable things. We don't need to know about the process in detail; we just need to know the effects. We can offer the way to improve the product; the way to distinguish what emissions the producer is causing, and what is already within materials. One manufacturer is only responsible for a small portion; they would like to know what. Therefore, we are not asking for the secrets of production. How do we convince producers to share this information? We can provide in exchange an evaluation tool which enables producers to know what percentage of emissions from a specific product come from their input, and what can be traced to other steps of production. They then have a means of comparison with other materials and products. Exchanging an evaluation tool for data seems to effectively convince producers to collaborate.

☐ The key point, however, is that industry data is quite simply the most desirable form of data. It can be supplemented by engineering calculations, and so on, but the basic issue is what source provides the best data. This is a separate issue from how to induce cooperation.

☐ Other reasons for producers to participate include: the fact that green propaganda is not believed anymore, so industry would like independent analyses; industry does not want old data to be used as it can be falsely incriminating, so they will share new data; and objective research can act as a propaganda measure.

☐ Problem is, it is only easy to get data from industry if it will show up well. So, whereas industry data is ideally the perfect data source, it is not always easy to collect all the data. Access is a problem. Also, how do you handle issues of confidentiality with respect to the future transfer of data? Industry will not share if they will be exposed. One of the most guarded secrets, for example, is how many cubic metres of a product can be derived from a cubic metre of material.

☐ Another problem is that you can only access data that people have to collect and measure anyways. So, while waste can be measured fairly easily, if waste water emissions of cadmium are not required, this information cannot be produced by the industry. Where do you collect information about non-required data?

☐ How do you balance data from the different input/output models? How closely do they meet in the middle? Energy is directly in the Input-output model in Germany, but not in Canada, where it is based on economic valuation. If they do meet, then the input/output model would be preferable if it has energy as a directly collected variable.

☐ It depends on which sector you are looking at. Whereas in administrative sector there tends to be a convergence of data produced by the two models, in commercial sectors there tends to be a divergence.

☐ You can only use the input-output model in a truncated form; you can fudge it. But you have to use process analysis to get a detailed analysis.

☐ Ultimately, partitioning output is only achievable through engineering analysis or economic valuation. The whole question of the allocation of credit is raised. For example, how do you account for how much energy is devoted to the operation of the factory (energy to operate fans), and how much went to production of a specific item or material. Response to this is related to fact that while in vertically-integrated industries (cars), it is almost impossible to allocate and disaggregate, it is much simpler in the building industries. Not many building producers make a large number of materials; most produce one material in 2-3 executions and distributions. In the building sectors we need information from simple manufacturers. Its not so difficult. Of course we have complex components but its not like cars. The chemical industry is nearly impossible: 10,000 products and one waste-stream.

☐ This latter point is more related to evaluation, however.

SESSION TWO: STRUCTURING OF DATA

POSITION PAPER:

1. Introduction

This paper is offered to focus discussion during the *Workshop on Data Structuring*. The paper addresses six key questions:

Issue 1: *Is a standardized structure required for organizing data in every building model? And if so, what is the ideal structure?*

Issue 2: *To what degree are different system limits needed to reflect the needs of user groups?*

Issue 3: *How should the costs and benefits of recycling be allocated?*

Issue 4: *What is the potential for modeling buildings like other consumer products:*

Issue 5: *Are any of the conventions and protocols established for energy analysis inappropriate for full life cycle costing of buildings?*

Issue 6: *What assumptions should be used for the scenarios?*

Within each of these six topics, additional questions are raised to further focus discussion. To stimulate thought and debate, some of the questions have been rephrased as propositions, and arguments marshaled *advantages* and *disadvantages*. The propositions do not represent the views of anyone in particular.

Issue 1: Is a standardized structure required for organizing data?

There are a limited number of elements from which all buildings are composed. Data structures determine the number of these basic elements, and how they are assembled, or `tied together'. Past efforts at organizing data on building elements, have indicated many hierarchies, with identical materials sometimes used in many different places and times. Because of this complexity, a model for impact assessments may require a highly flexible data structure, that permits users to partition the building from many points of view.

Can we agree on a single multi-purpose data structure for life cycle impact assessment? A common data structure means that every item - or functional unit - used to describe a building, is defined as a sub-set of the totality of units in the common structure. The benefits of such an approach are many. Sharing of data on manufactured products is much easier - which is a consideration for imported products especially. Results from different models can be integrated much easier. The infrastructure can easily accommodate new levels of detail in the data as these become available. However, if agreement exists on the need to produce a standard structure, how is the structure to be documented and formalized? Who produces a complete list of units for use in organizing building data?

How to cope with the complexity? Typically, as the building is broken into ever more precise units, the accuracy and flexibility of the modeling exercise improves, at the cost of increased complexity in the hierarchies, linkages, and restraints that must be used to qualify all of the data. The large number of potential applications for an impact assessment model, could mean that the data structure will become unwieldy. (Multiple terms needed for describing the same units, etc.) How can the structure be expected to accommodate so much detail?

Can regional differences be accommodated? Building materials and technologies are sometimes unique to specific regions. Is it reasonable to try to be universal with a description of the basic building units?

Is strict compatibility with existing data structures important? A number of market tested tools already exist to help in describing every element of a building, - CAD programs, cost estimating programs, programs for estimating operating energy requirements, etc.. Are linkages needed to accommodate the most popular of these programs?

How to limit the scope of the structure? Should the data structure be designed to incorporate data not directly related to specific units of a building? For example, community characteristics? local environmental conditions? occupant lifestyles? To some extent this depends upon the limits of the models used to analyze the data. Without a much better understanding of the kinds of models that are likely to be developed, how do we evaluate the suitability of a specific data structure?

Proposition

A single structure for organizing data on buildings should be developed and promoted for all impact assessment models.

Advantages:

☐ Easier data sharing between research groups

☐ Offers a kind of fundamental programming language that can be used to integrate results from many kinds of costing and modeling exercises.

☐ Saves time when trying to interpret or apply results from different models.

☐ Encourages more detailed and accurate modeling

Disadvantages

☐ Difficult to coordinate, administer, etc.

☐ Adds complexity

☐ Needs a agreed upon model in order to limit the structure

Issue 2: To what degree are different system limits needed to reflect the needs of user groups?

Most researchers involved with analyzing the environmental impact of buildings are working with a conceptual model of how the building interacts with it's surrounding environment. Ultimately we require a series of such models to address policy, planning and design issues, and to focus on the different concerns of tenants, owners, and the general public.

The challenge in developing a set of models is establishing appropriate system limits, and making these limits known. Sometimes it is possible to accommodate the views of a additional user groups by expanding the limits of the model. But this introduces greater complexity and additional data collection requirements. The ideal is to avoid complexity, and work on a limited number of simple models. Where do the current needs of potential user groups necessitate system limits that are different from the models now being developed? Some areas under debate are described below:

Should the building be separated according to responsibilities? A model must properly inform those who make the decisions. A common approach is to evaluate a building as a whole, despite the fact that it can be designed and operated by more than one group. The result is to integrate the cost data at inappropriate levels, blurring the important distinctions between, for example, the building/design team and the occupant/design team. Imagine a building that is designed and built to optimize resource use, and then leased by a tenant who "finishes" the construction in inappropriate ways (e.g., using toxic finishes, blocking natural daylighting and ventilation systems). The total impact for this building may be within the norm. However the critical information is how these impacts were influenced by the key decision making groups. This can only be known if the impacts are analyzed at two stages of production: construction by owner and construction by tenant. Should a general model, intended for optimizing selection of building materials, separate these key stages?

Is a separate model needed for analyzing indoor environmental impacts? Indoor air quality is a special concern, because it not only influences the ventilation energy load for the building, but also affects the perceived environment. Many potential user groups are very interested in using a model that can inform them about the air quality indoors. Ideally every model would allow users to evaluate the impact of building design on the health, safety and comfort of the indoor environment. Does the value of such information outweigh all the difficulties of collecting and organizing data on off-gassing rates of materials and their exposed areas, the sealing properties of finishes, ventilation effectiveness and so on?

Is a separate model needed for analyzing workplace environmental impacts? Contractors, trades, and factory workers are also affected greatly by the selection of materials for a building. Their health and safety concerns imply still additional inputs and outputs. Many workplace hazards are ostensibly addressed through regulations (e.g., required use of protective clothing). To what extent are these hazards relevant to the end users of the products, or to society as a whole?

Is a separate model needed for analyzing community environmental impacts? The impact of a building on the resource requirements of the surrounding community are of special interest to planners, but may also be crucial from a societal viewpoint. For example, consider:

- ☐ The transportation of people;
- ☐ The ambient energy available to other buildings; and,
- ☐ The quantity and quality of municipal services and utility infrastructure.

Each of these impacts can be affected in significant ways by building design, and can represent major environmental impacts. Is an analysis still useful if it ignores the community context?

Issue 3: How to allocate the costs and benefits from recycling

Recycled materials create a number of tricky problems for those developing and standardizing models. Some relate to the recycled content of materials used; others to the re-use and recycling of building materials themselves, after renovation and demolition has occurred.

How to avoid data proliferation? The highly varied amounts of recycled content in materials used for new construction add permutations to the basic data set. Can this variable be accommodated without exploding the data base? Using an average value for each basic material is one possible solution. But isn't it unreasonable to average the recycled content for whole categories of materials, when the actual range can vary from very small to 100 % recycled content for many materials - depending upon the source?

How to avoid double counting? If credit is given for recycled content up front, which is probably a good idea if the object is to influence design and purchase decisions, doesn't this prevent us from crediting a building for recycling the materials after use? Otherwise the end user of the material is unable to take credit for the recycling, because the benefits would be attributed to two different products. It is *not* fair to attribute the environmental benefit from use of recycled material to two products at the same time: the building from which it is sourced and the new product for which the material is desired.

How to include important environmental impacts in the analysis? By extrapolating current trends one might conclude that eventually the whole bulk of the building will be recycled - to some degree. The building is simply a "store-house" of materials. This raises the important issue of recycling hierarchies. How effective the recycling systems are at controlling emissions, relative to virgin material production. Some "recycling" is simply incineration for thermal energy - a fairly low value for resource recovery. Frequently it is possible for the building owner or demolition contractor to find superior end uses, if they are so motivated. The model cannot be of help in making the right decisions if it ignores the implications of alternate recycling methods. If the bulk of materials are recycled in dirty ways, just because they have low economic value, the negative impact of the buildings on the environment is potentially much greater.

How to reward designs that maximize waste recovery potential? Extra energy is required to design and construct a building in ways that facilitate resource recovery. And demolishing a building slowly, to exploit the best recycling possibilities, also requires extra time, money and energy. Without allowing some credit for recycling of the used materials, these desirable attributes of a building will actually increase the economic and environmental costs calculated by the model.

How to define a consistent methodology? Recycling of used building materials is a process that has direct inputs and outputs. To be consistent, the emissions and other costs should probably be allocated to the product that is being created, not the building from which the materials originated. So should the transportation costs. Essentially, as long as someone is willing to purchase the solid waste materials, they are not wastes, but new resources. This methodology becomes less clear, however, when solid waste disposal systems are examined in detail. Many materials are purchased, but only if delivered to point of use. Does transport then become a demolition cost? Hazardous waste materials are not well defined, and frequently cannot be separated from other waste. What assumptions can be made about the environmental impact of `mixed' waste? Solid waste is difficult to describe. Is the critical value weight, or volume, or the proportions of leachates and chemicals that may influence the disposal options?

Proposition

Limit the model to the input of recycled material and ignore the processes involved with recycling of used materials

Advantages

☐ Avoids double counting

☐ Avoids the need to define impossible scenarios

☐ Consistent with methodology used for products

☐ Reduces quantity of data required for each material

Disadvantages

☐ Underestimates the (negative) environmental impact of buildings

☐ Penalizes buildings that invest in recycling

☐ Ignores the value of waste management planning

Issue 4: What is the potential for modeling buildings like other consumer products?

The investigation of consumer products for purposes of environmental labeling or regulation, is a process that is occurring in many sectors of the economy. Is a building a special category of consumer product, that must be treated differently than the others? Some methodologies and concepts now being used for building costing (life cycle costing, eco-profiles, GARM) were originally developed for other products. Should a bigger effort be made to co-ordinate methodologies, and to share data with other sectors? Is it preferable to develop a shared data structure and a multi-product model?

Is there a choice? Where products under investigation by other sectors are also products that may constitute part of the building, or its subsystems, the amount of fundamental research work can be reduced. In fact the task of data collection is probably impossible without relying on product life cycle costing. The more similarity in methods and terms, the easier this becomes.

Are some types of buildings more suitable for generic treatment? No fundamental difference may exist between some types of buildings and many other products, except perhaps a difference in scale. Many small buildings are now manufactured completely in a factory. One-stop recycling depots for building materials are now common. In the future, buildings may return to the manufacturer for recycling at the end of their life, similar to what is now occurring for some appliances and even automobiles. The heaters, motors and other energy-using parts of buildings are sometimes regulated by energy efficiency legislation, in a similar way to the building as a whole.

Is the building an artificial distinction? Many products produced by our economies that are not now considered as part of the building cost, may be included as part of the building, depending upon the viewpoint. For example, the furniture, clothing, food and other materials that flow through a buildings are, to some degree, affected by the building design. Their effect is to simply add physical flows, during the operating stage of the building's life. Modeling such products is not significantly different from the energy transformations already modeled as part of the life cycle cost. A multi-product model would accommodate this larger view of building resource use.

Three key differences between buildings and other consumer products are summarized below:

Longevity	Building lifetimes are typically 40-80 years. In some cases the structure will persist for hundreds of years. Such lifetimes are far in excess of other consumer durables. the result is a uniquely slow turnover rate (1 to 2 % annually), a large number of recurring costs (often in excess of the original capital cost), and an extensive amount of product redesign and retrofit. The building sector as a whole consumes 20 to 30% of all resources in the economy. For these reasons the impact of current design decisions can have an inordinate impact on our future environmental quality.
Complexity	The variety of materials and products used by a building can itself place a limit on the selection of data acquisition strategies and modeling techniques. A single house can use 70 to 80 basic types of materials, which are in turn manufactured into thousands of building products and components, each with its own energy intensity and life span, and some with the added impact of affecting the building direct energy requirements for heating and cooling.
Resistance to Change	The pace of technological change within the building industry is slow. Typically building innovations require 10 to 20 years to be adopted by a majority of trades. Many parts of the building sector are still operated as a craft industry, with small contractors and tradesmen determining how products are assembled. The industry is regulated by a number of jurisdictions, which have generated numerous product standards and labor regulations. Standards are not evenly enforced, and have traditionally avoided issues other than health and safety. Consumers of new buildings have historically not shown concern for energy and environmental features, and in the case of leased buildings, are not in a position to exert much pressure on the marketplace. There is no quick production-line fix, no single standard to be re-issued and proclaimed. For all these reasons it is difficult to translate research results into better buildings. A special effort is required, both to identify alternatives that are practical and effective, and to develop tools for optimizing decisions by a diverse group of participants.

Proposition

Buildings are unique products that should always be modeled separately from other consumer products.

Advantages

- ☐ Significant differences in life & complexity
- ☐ Buildings need to be costed and modeled by many more groups in order for change to occur
- ☐ Aside from common data sets, no need for co-ordination

Disadvantages

- ☐ Synergy
- ☐ Consistent terms, methods, etc. may assist planners, and other with larger viewpoints

Issue 5: Are any of the conventions and protocols established for energy analysis inappropriate for life-cycle impact assessment?

During the 1970s and 80s conventions were established for energy analysis.[16] These included, for example:

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[16] *International Federation of Institutes for Advanced Study*, 1974 Energy Analysis Workshop on Methodology and Convention

☐ Definition of levels for categorizing the limits for direct and indirect inputs during production;

☐ Terms for differentiating between resources ("free energy", gross energy requirements, etc.); and,

☐ Conventions for which types of energy are worth calculating (human labour is normally excluded as are ambient energy sources).

The life cycle impact assessment of buildings is largely an extension of this exercise. There are some good arguments for continuing the traditions:

☐ The bulk of the data available on resource use has been generated according to existing conventions.

☐ The impacts associated with energy transformations are the greatest part of any building impact assessment. Over 80% of the environmental impact of buildings in such areas as air quality, carbon emissions, & use of scarce resources, is caused directly by energy consumption. If we get the energy right, most else will follow.

Are there areas of analysis, however, where traditional approaches are now inappropriate, or irrelevant?

Energy units or Resource units? Lutzkendorf proposes that energy be treated like any other resource, rather than converting all resources into energy units.

Do transportation costs need more discrete inputs? A number of suggestions have been put forth for separately tracking transportation costs. The conventional approach has been to include these in the energy intensities of a product.

Do we need conventions, or better documentation? Despite attempts to follow conventions in energy analysis, much of the previous research work is inconsistent or ambiguous about the system limits and assumptions. Is better documentation of models, and a more sustained research effort, likely to resolve any problems with different methodology? Are conventions still necessary?

Issue 6: What assumptions should be used for the scenarios?

All of the data used for calculating resource costs during occupancy, including the repair, and renovation activity, must be based on scenarios. The operating energy for most buildings far exceeds the embodied energy. And many buildings will consume more resources, and a different mix of resources (more carpets, a lot less concrete), as part of the on-going repair and replacement activity than during the initial construction. The development of realistic scenarios is therefore critical to the results of an impact analysis. What assumptions are suitable for establishing the scenarios?

Is the future an extension of the present? The traditional and most convenient approach to projecting energy use in buildings is to assume a future load equal to the existing conditions. This type of assumption may no longer be suitable, as the focus is altered from pay-back analysis, to resource use and environmental impacts. For example, the vast majority of buildings will receive retrofits that improve the energy efficiency of the heating system, envelope, lighting etc.. Also the interior finishes are certain to change frequently. A realistic impact analysis requires that some judgments be made about how these retrofits will improve performance. Just like computer technology, many aspects of building technology are part of a trend that is allowing buildings to upgrade economically. Windows, for example, do not normally last the life of typical building, and we can be fairly certain that the new windows will perform better than the existing. Should those buildings that are designed to be "retrofit-ready", receive credit for taking advantage of improved technology when it becomes available?

Should restraints be imposed if resources are scarce? In most parts of the world, fuel mixes cannot remain the same because of moratoriums on nuclear plants, a scarcity of natural gas, a lack of additional hydro electric potential in a growing economy, and so on. So why pretend they will? This only distorts the impact analysis. As part of a common data set for buildings, do we need to list assumptions about the availability of resources, and the expected regional energy mix?

Should the repair and replacement rates for components of a building be based on past performance? Assumptions about material lifetimes are very difficult to validate. A lot of material failures occur as a result of abuse, or faulty system design, and do not reflect inherent qualities of the material. In many cases the life time of a material or assembly is determined by its technical obsolescence, which is also not an inherent quality. Moreover some materials, particularly the mechanical systems, have changed radically over the last few years, and have no track record. For all of these reasons it is possible to reach very different conclusions about the life time material requirements. Is it reasonable to trust producers of materials to establish the expected life spans? What kind of justification is required for scenarios about repair and replacement rates?

Proposition:
Projections of direct energy required for building operation shall be based upon the as-built energy load and present day mix of fuels

Advantages
- ☐ Avoids highly speculative conclusions
- ☐ Less political debate required
- ☐ Emphasizes the importance of initial design decisions, which are also the decisions most easily influenced

Disadvantages
- ☐ Certain to be less accurate than considering trends and resource limitations
- ☐ Distorts the impacts in potentially dangerous ways.

Table 1: Some Examples of how data can be organized within the model

Production of a building material	Construction of a building	Components of a building	Examples of the Components
Resource Extraction	Site preparation	Categories (CRB)	Super structure
Processing	Preparatory Work	Sub-categories	Exterior Wall
Fabrication	General work to Building Structure	Sub-elements	North wall
Wholesale	Sub-structure	Components	framing
Retail	Super -structure	Ingredients	studs
	Services	Resources	timber
	Special Equipment		
	External Structure		
	External Areas		
	Main Services		

ISSUES RAISED IN WORKSHOP DISCUSSIONS

How do we use existing data which is poorly quantified?

☐ Important question is one of how old data is approached. Is existing data usable as a base, or is it useless? It is not clear whether old data takes into account the limits that are being used today. But perhaps the use of old data is better than nothing.

Data may need to be quantified as to how it may be used

☐ Need to qualify what end use of the data is; different means are used for different ends. For example, what is more important, embodied energy or human safety? How the energy and material flows are described depends on the purpose of the values being sought.

☐ The reason the data is sought should always be specified; in some cases an average may be suitable, and in other cases misleading. For which decisions and choices are averages acceptable? One proposal is that best data be used for those products and processes which change quickly and average for those which change slowly. When choosing between materials it is important to establish which kind of question can use average values and which question requires specific measures.

What kind of rating systems are most appropriate for data or building materials?

☐ It is difficult to qualify the quality of data. How do you rank the data being used in terms of reliability? If you're using data from a variety of sources, it is important to be able to alert user to questionable data and highly-trusted data. When you have a degree of unreliability, how do you store and qualify the data that communicates this uncertainty?

For example, one system that is used is a 0 - 10 scale, on which data and source reliability is measured, based on personal experience, etc.

☐ It doesn't all have to be numeric, however; qualitative descriptors that go with numeric data are very useful.

☐ How do you characterize data that is needed in order to achieve a specific outcome for a certain product? How do you balance amongst the issues such as energy, pollution, sustainability? For example, what is the important information to include when examining tropical hardwoods?

☐ In the end, the decision is subjective, and comes down to the perceptions and judgments of the design team. As a designer, it is a duty to select 2 or 3 of the parameters that you think are appropriate, and go with them with the hope that your judgment and estimation is based on clearly-thought out values.

☐ But the designer doesn't have time to get involved with the minutiae; only the bottom line. In terms of presenting end results, the designer can't take the responsibility of giving a number; a range is more appropriate. One clue as to how we may deal with this; we need a bottom line. If 3-13 is a range, is it good enough to average this or do I need to know more? You can't give a number.

☐ It is important that validity is given to methodologies and data in the form of guarantees. Where will these come from? Designers want to have some criteria. Hopefully there is some quantifiable data; what is the quality of it?

☐ In the end, however, whatever criteria you use to specify a material is ultimately a subjective decision, which is hopefully based on reliable quantitative data. So what indicates the quality of the data you are basing your decision on? For example, what tells you that if one value is 100 and another is 110, the 100 value doesn't have a margin of error greater than 10%?

☐ The result is sensitivity analysis to judge data; a qualified judgment based on personal experience. We need some standard by which to compare ourselves. Suggestion is that we can compare to a duplicate data set.

☐ Speculation that it is dangerous to give a 1-10 rating. It may be better to give an additional textual comment rather than a rating on data values. Give a comment, source and address, and people can go check the data themselves.

☐ There is, however, a big difference between researchers and end users, the latter requiring no more than a rough number. For design professions a description of a qualitative nature may be as important as numeric.

How to cope with innovators and non-associated businesses?

☐ Industry associations are going to have to play a key role in terms of setting parameters and values and providing guarantees. This raises the question of how to deal with areas of the building industry in which products are made by manufacturers not affiliated with an association. If associations came out with general values, individual innovators not represented or regulated by an association would not be impeded from saying that their product is better.

Discussion on techniques for improving data sharing

- ☐ What can be done to facilitate data sharing? Perhaps if a specification sheet with a similar layout and common minimum and optional data were used, this problem could be overcome.
- ☐ But how do you deal with the problem of conversion of measurements? Do we need a guide to indicate how to change from actual to nominal values? A protocol for common conversion would be necessary.
- ☐ This raises the issue of international data sharing. The linguistic translation process itself muddies the ability to convert. Furthermore, there exist differences in the way materials are used intra-nationally.
- ☐ This question of data sharing begs a further question of sharing amongst different sectors, rather than between different nations. Sectorial sharing is as important as geographical sharing.
- ☐ One viewpoint is that while it is conceivable to have a basic data set, there is not adequate funding for this. Who will organize the accumulation of basic data? Who will pay for it? It is necessary to organize pressure for a change in values and for the governments to act.

Difficulty of sharing data between nations

- ☐ A further viewpoint is that the nation level is the appropriate level at which to share data. You can't share data across borders; only structure and methods. In other words, you can share common assumptions, but not data values.
- ☐ This brings up question of how to establish values for imported products? If there are not common assumptions or data sets, then it is very difficult to admit foreign data values for imported goods. Is it possible to add values from different nations, when questions that were addressed may diverge?
- ☐ Perhaps a mechanism to overcome this would be to disregard the actual values, and evaluate how much energy or emissions would have been entailed if the product had been manufactured in our own nation.
- ☐ How do you deal with instances in which countries can declare, for example, reduced emissions because they import the goods? This just transfers the values. For example, if the UK has reduced carbon emissions because it now imports a lot of steel, is the UK meeting its Rio target? What contribution are they having indirectly on emissions? How do you measure this?

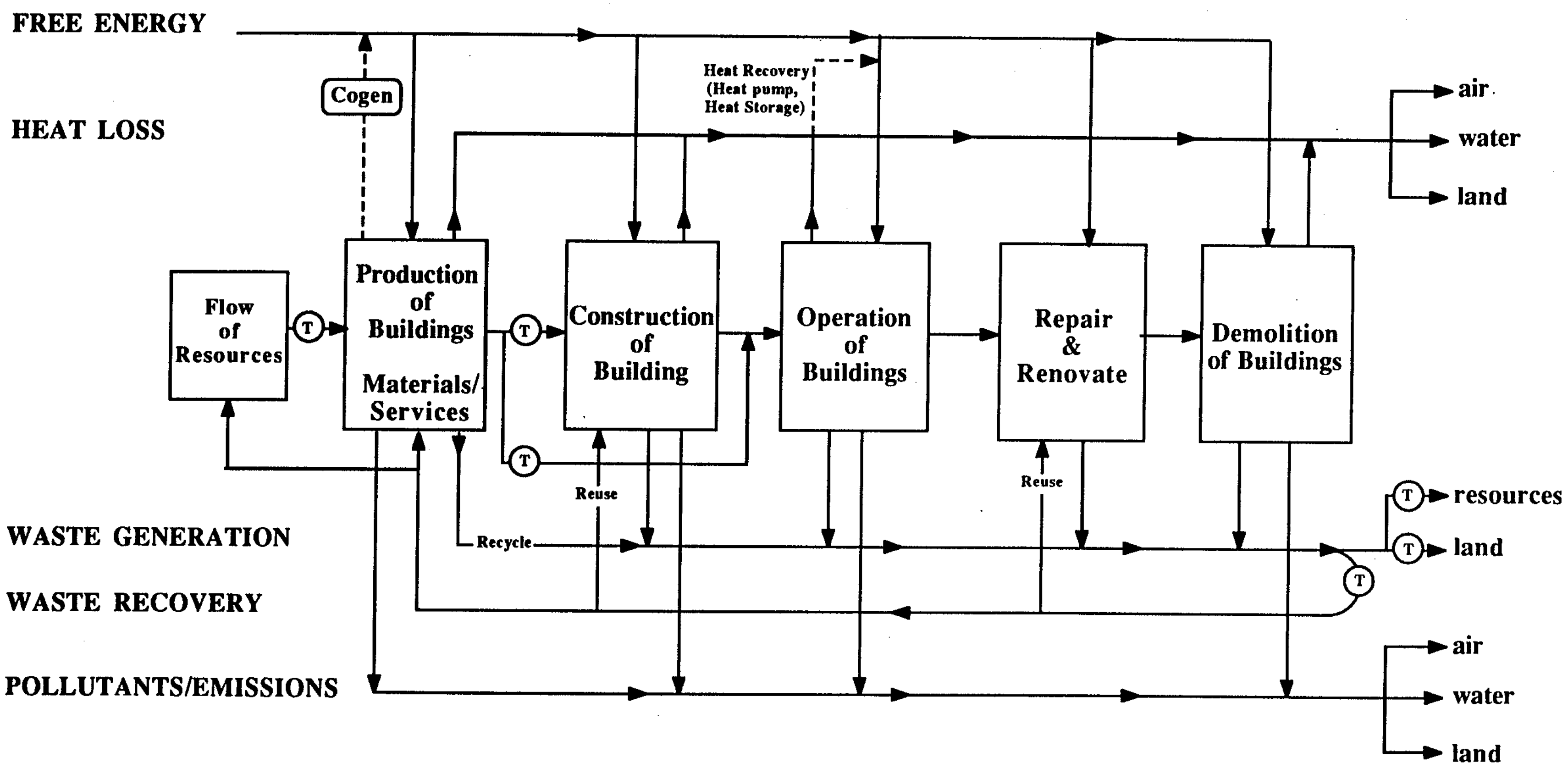
Structuring data on recycled materials

- ☐ An important question is the continuing problem of how to cope with recycled materials and how they are accounted for in the data structure for a model. Design optimization is greatly impacted by how you deal with recycled products. The boundary is no longer input/output, but input/output/input. There should be recognition of the complexity of the recycling process.
- ☐ Recycled materials cannot be credited as benefits as both inputs to the building and outputs from building demolition. Should the convention be to give recycling credits up front? If benefits are credited at the beginning, however, how do you give credit for disassembly that is sustainable? If you make a block out of garbage waste, is there no

energy usage declared? A current convention is to give original manufacturer half the credit and the recycler half the credit.

- ☐ Building industry is different from containers as longevity is involved. You need two sets of figures: one for designers addressing realizable benefits, and another set that addresses potential benefits. Don't combine them. Recycling represents an option, a potential, but you don't actually know to what extent this potential will be exploited.
- ☐ We can recycle building parts; saving energy. But don't subtract the energy saved from recyclability; give qualitative information instead.
- ☐ Its more complex; you need to look at the form of the material. Composite material is problematic, simple material is easier.
- ☐ We need to know more about replacement. We don't know enough. Lets just say this component has a good chance to be recycled and in this way account for recycling in the future.
- ☐ How important is it to construct a model that accounts for the future in terms of quantitative information to do with recyclability? You must count the overall biomass that was cut.

General Model Showing Quantifiable Flows at Each Stage of Analysis (Adapted from Kohler)



Ⓣ = Transportation Energy Input/Output

SESSION THREE: EVALUATION METHODS

POSITION PAPER:

1. INTRODUCTION

This paper is offered as a means for participants to focus discussion during the Workshop on Evaluation Methods. The paper addresses three key questions:

Issue 1: Have we considered the full range of evaluation methods that are now available, or that may soon become available? And have we correctly identified their relative strengths and weaknesses?

Issue 2: In what areas do all such evaluation methods tend to produce misleading results? And what strategies are warranted to minimize inappropriate interpretation of the results?

Issue 3: Where are the opportunities for coordinating research work on refining evaluation methods?

Issue 1: Have we considered the full range of options available, and their relative strengths and weaknesses?

Leuridan and Kohler have provided an overview of most standard methods available for evaluating the impact of buildings on the environment. These have been summarized and extended in *Table 1*. The table includes an outline of the strengths and weaknesses of each approach.

As we review this summary table, three important questions emerge:

☐ *Is the list of methods complete?* Are other methods - or variants or combinations of these methods - currently available for consideration?

☐ *Will new inventory techniques create possibilities for improved evaluation methods?* For example, consider the creation of Input-Output tables with emission quantities, (as presented by Hohmeyer). Or consider the development of ecological footprints for different types of resource use, (as presented by Rees).

☐ *What can be done to address the weaknesses of the methods?* Each method has it's limitations. However, these limitations may not be relevant for specific applications. Are some methods particularly well suited to certain policy, planning and design decisions? It may be possible to compensate for the limitations in the near future. Are some methods completely inappropriate for the analysis of buildings?

Table 1: An Overview of the Evaluation Methods, their Strengths and their Weaknesses
Part 1: Output Methods

Method [& units]	**Summary Description**	**Strengths and Appropriate Applications**	**Weaknesses**
Mass, Volume & Energy Balances [kg] m3] [J] [L]	Emissions from all processes at each stage of production are quantified and aggregated without any weighting: Atmospheric emissions (kg) Waterborne wastes (kg) Solid wastes (m3) Raw materials (kg) Energy (J) Water (l)	☐ Simple to understand & execute ☐ Transparent to users ☐ Suitable for quick rough cut assessments ☐ May also be suitable as general indicators of impact if validated by other, more sophisticated methods	☐ Difficult to interpret significance ☐ multiplicity of factors ☐ easily misleads due to order of magnitude differences
Limits: ☐ critical air volume [m3] ☐ critical water volume [m3] ☐ solid waste [kg]	Data is aggregated by vector: Air, Water, Soil. Substances are weighted with their respective emission limits, prior to summing.	☐ transparent to users and applied without difficulty ☐ powerful image for public mind ☐ no confusion of air emissions with the high mass - low impact water and land emissions	☐ Limits not always available ☐ limits set legally may vary by jurisdiction ☐ limits may not reflect actual impact on environment or health but only what is practical or affordable ☐ many substances move through the vectors as they are transported, (air particulates -> soil contaminant -> water pollutant).
Material Flows: Eco-factors [1/Fk F/Fk C] or Ecological Footprints [m2]	Emissions and resource flows (Fk) are related to the capacities limited by nature (F). Nature's capacity is the total available resource (in the case of non-renewable resources), or the carrying capacity of the ecosystem (for renewable resource use or activities depending on ecological processes). A variant of this approach calculates the area of given ecosystems required to sustain a given life support functions.	☐ can be used to derive a single value ☐ is a fundamental approach since it relates the building to the theoretically absolute limitations ☐ is especially valuable for making broad comparisons, and for encouraging more responsible attitudes ☐ can be easily corrected to reflect improvements in our understanding of environmental impacts	☐ requires lots of data collection, since all the flows need to be added in order to derive F. ☐ Carrying capacity, available resources, and other Fk values are contentious issues, that depend on value judgments, and are still largely guesswork ☐ Some kinds of emissions are undesirable at any level, and cannot be related to sustainability
Costs of Control or Substitution [$]	Emissions and resource flows are converted to monetary values based on the cost that would have to be borne to control the emission, or to substitute alternate technology	☐ dollar values are easy to integrate with other types of evaluation, ☐ facilitates cost optimization ☐ especially useful in cases where damage costs are difficult to estimate (e.g., global warming)	☐ requires difficult assumptions about the effectiveness and cost of specialized technology ☐ reasonable limits do not always exist for establishing the extent of controls required ☐ control costs may bear little relation to actual cost of damage to society

Table 2: An Overview of the Evaluation Methods, their Strengths and their Weaknesses
Part 2: Effect Oriented Methods

Method [& units]	Summary Description	Strengths and Appropriate Applications	Weaknesses
Potential Contribution	Effects of concern are chosen, (global warming, acidification, urban smog, human health, etc.) and each is carefully defined with regards to how different substances contribute to the effect. A conversion factor is established for each substance, such that quantities can be weighted scientifically. The potential contribution from each substance is then added to obtain a total contribution the building for the effects of concern.	☐ useful for describing multiple effects from a product or building without reference to their transport mechanisms (air, liquid, solid). ☐ organizes information in ways suitable for many user groups; ☐ can easily incorporate site specific impacts by defining effects at the local level	☐ no consensus exists for what conversion factors to use for each substance and effect; ☐ no clear delineation of effects has been proposed, and some effects can be differently defined depending on the individual; ☐ expresses the building's potential contribution to an effect, not the real impact of the building. ☐ assumes a linear relationship between cause and effect.
Willingness to Pay, Willingness to be Compensated **[$]**	An economic value is determined proportional to the environmental risk associated with the balance of emissions for each substance. The value of the risk is equal to society's willingness to pay to avoid the risk (or to be compensated for the possible damages). Market prices are used where possible (e.g., timber losses), along with a range of valuation techniques used by economists.	☐ all costs can be aggregated to a single value ☐ addresses the issue of greatest concern - the damage to are social and life support systems; ☐ combats the tendency of economists and policy makers to ignore environmental impacts because they have no market value.	☐ non-priceable effects are still left out of analysis ☐ aggregation and rounding errors can lead to false estimates of zero cost when large numbers of persons experience small amounts of damage ☐ not transparent to users, hides many types of trade-offs ☐ use of the monetary value leads to much debate over appropriate discount rates for human health, life, and use of scarce resources.
Others?			

Issue 2: In what areas do all the evaluation methods tend to produce misleading results? and what strategies are warranted to minimize incorrect interpretations?

Most approaches to evaluating environmental impacts of buildings have difficulty defining the effects of certain types of emissions, and comparing them with other effects, even when the effects are quantifiable. Some examples have been cited by Leuridan and Kohler, and have been listed below. The issue is how to either incorporate methods for evaluating these impacts, or how to avoid misleading users when such impacts are not included in the analysis.

☐ *How to evaluate emissions related to the building operation and performance?* Valuation methods begin with an inventory of flows associated with the building. With the exception of the direct energy requirements for lighting, cooling, etc., the flows are inventoried from the aggregation of a unit oriented data base. Those environmental impacts that are a function of how the building operates as a system, cannot be derived from such a database, and are hard to predict. For example, no simple models are available for assessing the relationship between building design and sound output, or the intensity of extremely low frequency radiation, or the concentration of volatile organic compounds from off-gassing of finishing materials, or the loss of negative ions from use of metal ductwork to move air, and so on. Can an impact analysis be qualified so users recognize such limitations?

☐ *Can every building impact evaluation be expressed in a way that clearly communicates the limits of the analysis?* Is it possible, for example, to simply state:

- Which Stages of life are considered;
- Which Substances have been inventoried; and,
- Which environments have been included.

☐ *What is the best way to address impacts resulting from the emission of unusual substances?* The highly toxic nature of some unusual emissions may require their consideration as part of an environmental impact analysis. Examples include the heavy metals, persistent organic compounds, asbestos particulates, radiation. These substances may not be inventoried because they are rare, or they may be overlooked because they are indirect outputs related to auxiliary processes, (e.g., spraying saw mill machinery with pentachlorophenol), or related to interactions between the emissions and the environment (eg., inorganic mercury emissions are methylated by microorganisms, and become concentrated in the food chain). How can a general evaluation method accommodate such important impacts?

☐ *Should an effort be made to err on the side of environmental protection?* The lack of available data on many emissions, means that the environmental impacts of a building will be consistently underestimated. This will be true for all buildings, but is especially a concern for products or buildings where data is scarcer than normal. For example, new products where processes are poorly defined and indirect inputs are unknown; or renovated buildings where many of the material quantities are unknown. A better approach might be to adjust the impact assessment so that the results always err on the side of a safer, healthier environment, (at least until more data becomes available on emissions). How can estimates be adjusted to become `environmentally conservative'?

Issue 3: Where are the opportunities for coordinating efforts to compare and refine evaluation methods?

Leuridan and Kohler have described a research project which involves application of a variety of methods to a cross-section of the building stock. The object is to compare the results of different methods, and ultimately, to derive indicators of environmental impact. Presumably, a similar process is likely to take place amongst other research groups, as data on building materials is accumulated and used to develop suitable planning and design tools. In advance of this research, some questions need to be answered:

☐ *How much field research is warranted?* Without detailed case studies is it possible to evaluate the different methods?

☐ *Do certain types of buildings warrant special attention?* For example, in terms of the potential environmental impact, the upgrading of existing buildings may be more important than design of new buildings; housing may be more important than commercial buildings; larger buildings and larger developments may be more important than small projects.

☐ *Can building archetypes be established for reference in the future?* Archetypes can be useful when attempting to calibrate different evaluation methods. If properly defined, the archetypes can also become very useful as an aid in educating designers, and as a basis for making policy and planning decisions.

☐ *Are there key features that should be part of every evaluation method?* An evaluation method is more effective if it successfully addresses the environmental impacts of greatest concern at present. Can these principle concerns be identified? Some possibilities include:

- *Global warming and climate change:* Building are particularly energy intensive commodities, and are likely to play a major role in strategies to off-set global warming.
- *Fugitive emissions:* Those emissions that cannot easily be contained or controlled, such as air emissions, are of greatest interest to the impact analysis. Those emissions that can be controlled, like solid waste production, or water consumption, are more effectively addressed through regulation and other policy instruments.
- *Human health impacts:* The effects on human health are of fundamental concern, and sometimes represent the greatest social cost. For example, the California Clean Air Act, which sets targets for phasing out gasoline powered vehicles in the Los Angeles basin, became law only as a result of careful accounting of human health costs associated with urban smog.
- *Monetary values for externalities:* Although monetary values may not be particularly useful for designers or owners of buildings, they may be necessary for establishing appropriate levels of energy efficiency in building codes and standards, and for making policy decisions in such areas as energy supply strategies, and taxes on resource consumption.

ISSUES RAISED IN WORKSHOP DISCUSSIONS

Clarifying the methodology

☐ There are two types of models: the first type aggregates all the environmental impacts based on the medium the impact occurs in (i.e., water, land, air). This type may also express the ratio of quantity relative to carrying capacity. The second type expresses the effects effects associated the emission or material. It is necessary to indicate which method/model is being utilised. It is also necessary to specify parameters; for example, what issues are included? is every stage of a building's life accounted for? are all environments (indoor, community, regional, global) included?

Valuation based on degree of risk

☐ Risk assessment methodology is necessary even though this has been devalued due to misuse by the nuclear industry. A risk assessment methodology would be valuable for a design professional. Could use an A-B-C scale, with headings for risk being slight/ moderate / unacceptable. This is seen by some as overly-crude structuring.

☐ The risk assessment method using human toxicity is convertible into dollars and we can value a human life.

Most "effects" cannot be added to each other, but they can be traded off. Which is most important?

☐ Other evaluation methods include eco-factors, which denote effects in term of tolerance and carrying capacity. But these methods analyze effects without providing anyway of aggregating. A more appropriate option is multi-attribute tradeoff analysis. The latter starts to weight things.

☐ Regulators, manufacturers and the general public often need evaluation in one-dimensional dollar terms, while designers and researchers require effects evaluation in terms of multidimensional environmental values. We are caught between two extremes: the detailed level and the simpler needs of practitioners who prefer a few set of rules to follow.

When different effects are considered, how do we establish priorities?

☐ We need a rational method of weighting priorities. There is a difference between pinpointing embodied energy, and establishing environmental sensitivities as an end goal. There is no absolute value for balancing these two out. How do we rank priority effects? Global warming then ozone depletion? Do people start from the right page? For example, many building designers now ask about off-gassing when they should be considering energy.

☐ A very difficult set of value judgments are required which will provide a hierarchy of decision-making. The people who are going to be using the buildings are the ones who should partly set the priorities.

☐ Damage control analysis should be included as a criterion for evaluation.

Future Research on Valuation

☐ Possibly the evaluation method that is the most effective is that which in some cases translates effects into dollar values; for example, human health costs, compensation / damage costs.

☐ We can try to calibrate methods according to how they evaluate archetypal models or buildings.

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