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MACRO MATERIAL FLOW MODELING FOR ANALYZING SOLID WASTE MANAGEMENT OPTIONS

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INTRODUCTION

A Macro Material Flow Modeling (MMFM) concept and approach are being adopted to develop a predictive modeling capability. This capability is intended to provide part of the basis for evaluating potential impacts from various solid waste management system configurations and operating scenarios, as well as evaluating the impacts of various policies on solid waste quantities and compositions. The MMFM capability, as part of a broader Solid Waste Initiative at Pacific Northwest Laboratory, is intended to provide an increased understanding of solid waste as a disposal, energy, and resource problem on a national and global scale, particularly over the long term.[1]

This model is a macro-level simulation of the flows of the various materials through the solid waste management system, and also through the associated materials production and use system. Inclusion of materials production and use within the modeling context allows a systems approach to be used, providing a much more complete understanding of the origins of the solid waste materials and also of possible options for materials recovery and reuse than if a more traditional "end-of-pipe" view of solid waste is adopted.[2]

The MMFM is expected to be useful in evaluating longer-term, broader-ranging solid waste impacts than are traditionally evaluated by decision-makers involved in implementing solutions to local or regional solid waste management problems.

This paper discusses the types of questions of interest in evaluating long-term, broad-range impacts from solid waste. It then identifies the basic needs for predictive modeling capabilities like the MMFM, and provides a basic description of the conceptual framework for the model and the associated data. Status of the MMFM implementation is also discussed.

TYPES OF QUESTIONS OF INTEREST

There are at least two types, or levels, of solid waste decisions or concerns:[3]

- The first type of decision or concern is related to **immediate or near-term management issues**. They most frequently involve planning and operation of facilities and equipment within an existing institutional and policy framework. These are the issues generally dealt with by local officials, such as siting new landfill space, forestalling the need for new landfill space by instituting material recovery activities, siting and licensing solid waste incinerators and waste-to-energy facilities, and the like. Many efforts are under way to address these near-term issues, both within the U.S. and abroad.[4]

- The second type of decision or concern is related to **long-range or policy issues**. Included at this level are national resource management policy, long-term land-use decisions, cumulative long-term environmental changes, sustainability of materials use and disposal practices, long-term economic impact, etc.

The focus of this paper, and of the MMFM concept and approach described in it, is on the latter type of decision or concern: the long-range policy issues. By effectively addressing the long-range issues, it is hoped that the reactiveness associated with the near-term management issues may be reduced.

There are a variety of different types of long-range policy questions that may be of interest pertaining to solid waste management and planning. These questions can be grouped into a relatively concise set of question categories, as discussed below.

Waste Quantities and Timing

What quantities of solid wastes will be produced, and when will they occur? This type of information is important to gauge the magnitude of the problem, the relevant trends over time, and the appropriate types and capacities of facilities and infrastructural elements (such as transportation capabilities) that will be needed to cope with the waste material. At the local level, such information is also useful for determining how waste flows should be routed from the sources through the various components of the solid waste management system.

In order to fully understand waste quantities and timing, it will also be important to understand the functions that result in the production of the wastes. These functions are discussed further below.

The waste quantity information must be available in a form that allows further breakdown into appropriate categories as needed to study particular issues. Such categories might include the type of the waste (either by regulatory designation or physical/chemical characteristics), the sector or sub-sector of the economy generating the wastes, and the region or population group from which the waste is anticipated to arise.

Waste Compositions

What are the physical and chemical components of the solid wastes? Into what regulatory categories can the wastes be classified? How uniform or heterogeneous are the wastes? Such information is needed to determine potential impacts of the wastes, to define appropriate management and disposal options, to evaluate the potential effectiveness of different options, to determine potential regulatory constraints, and to provide a basis for examining alternate system configurations and strategies (see below).

The waste composition information must support further breakdown into appropriate categories in the same way as the waste quantity information discussed above.

System Costs and Economics

What are the costs associated with operation of the solid waste management system, and of the related elements of the materials production and use system and the energy system? How are those costs allocated among the various system functions? How can they best be balanced within the system, given the waste quantities and compositions to be handled? Such questions are important in determining the relative economic efficiency and financial viability of the current system and of various alternate system configurations and strategies. Although costs are often an overriding consideration in near-term decisions, little emphasis is currently given to long-term economic considerations, particularly at the broader level. This is because current solutions are primarily being developed locally, to respond specifically to local needs.

Long-Term Environmental Impacts

What are the impacts associated with the operation of the solid waste system, and how can these impacts be mitigated? What is the ultimate fate of various constituents of interest (e.g., heavy metals or released gases) contained in the wastes or resulting from decomposition of the wastes? What are the trends for the future, based on the current system configuration? Such questions address the potential long-term environmental and ecological impacts that may result from various solid waste practices. Indirectly, they also address the sustainability of the current practices over the long term.

Because of the way the solid waste system interconnects with essentially all societal activities, it is affected by and affects a number of other issues of concern. As an example, solid waste issues are interconnected with global environmental issues in several ways:

Combustible solid wastes may be used as a fuel source to replace or supplement conventional fuels. This hastens conversion of the contained carbon to carbon dioxide, as compared to landfilling, but may replace some fossil fuel use that would also contribute to increasing the global inventory of carbon dioxide. Furthermore, other pollutants released by burning solid waste will differ somewhat from those released by burning fossil fuels. At the same time, the use of combustible solid wastes as fuel would reduce landfill requirements somewhat, and would change the form of the waste being landfilled by replacing the material used for fuel with a much smaller volume of ash.

Decomposition within landfills produces methane and other gases that are slowly released to the atmosphere. This methane could, in many cases, be collected for use as fuel. This landfill methane, which often is released unused, could then replace other fuels, thus reducing the total carbon release to the atmosphere.

In addition, improper management of specific wastes can result in the release of harmful or potentially harmful materials (e.g., chloro-fluorocarbons or CFCs, heavy metals, or PCBs). Thus, solid waste management can contribute to, or help to mitigate, potential global environmental impacts.

Opportunities for System Improvements

While an important part of the needed analytical capability is to assess the current solid waste system, it is also important to be able to assess possible changes from this baseline configuration. Several types of possible system improvements are important to consider:

a) **What potential opportunities exist (or may exist in the future) for material diversion?** Materials may be diverted for a variety of reasons, including waste volume minimization, resource and/or energy recovery, and isolation of specific waste types for special handling or treatment.

b) **What potential opportunities exist (or may exist in the future) for improvements in the basic technology elements within the system? How would such improvements affect the costs and impacts associated with the system? Which improvements, in which combinations, would provide the greatest benefits? How are these opportunities sensitive to changes in the underlying configuration or operation of the system?** Answers to such questions would provide considerable guidance to technologists seeking to develop and deploy improved technologies for use within the solid waste and associated material flow systems.

c) **What aspects of solid waste system operations represent the greatest impacts on the environment, and how can these functions be better performed to reduce impacts?** Improvements in needed solid waste management functions could at least partially mitigate impacts resulting from the system. Understanding those portions of the system that cause the greatest impact will provide a better focus for improvement efforts.

Indirect Impacts of Policy Alternatives on Solid Waste

What will be the impacts on solid waste quantities, compositions, or practices of various policy alternatives being considered? Many policy decisions or alternatives, though not directly aimed at solid waste or materials production and use, will still have impacts in these areas. Examples are economic or regulatory policies that result in shifting industry or consumer preferences for various types of products or materials. Improved understanding of the relationships and the dependencies between the solid waste system and other societal activities would help predict how solid waste activities would be affected by such indirect influences.

THE NEED FOR PREDICTIVE SOLID WASTE MODELING

To effectively address any of the types of questions discussed above, a minimum need is to be able to calculate and predict material flows throughout the material production and use systems and the associated solid waste system. Therefore, the development of a Macro Material Flow Modeling (MMFM) capability was identified as a priority. Development of the MMFM will provide an integral part of the basis for a predictive capability to address solid waste problems and issues at the broadly based policy level. (Such an ability to predict or simulate material fluxes within society has been previously identified as an important element of a major effort proposed to understand the full range of human impacts on our environment.[5])

To include all of the relevant drivers that affect solid waste production, management, and disposition options, the MMFM must extend beyond just the components of the solid waste management system to encompass the whole materials production and use cycle.

Although the MMFM or similar capability is necessary to answer any of the types of questions discussed above, it is not sufficient in and of itself to directly provide answers to many of these questions. Therefore, some additional capability will eventually be required to extend the MMFM to evaluate specific types of impacts. This additional capability might potentially be incorporated in a suite of external processing routines to accompany the model, or might be carried out entirely separately from the model. Decisions regarding the eventual implementation of these extended capabilities remain in the future.

In addition, it may be desirable to link the MMFM to other external sources for access to parameters that indirectly relate to solid waste. Such parameters are related to economics, populations and demographics, regulatory and policy issues, and the like.

Figure 1 schematically illustrates the potential use of the MMFM in conjunction with other models and capabilities to predict the full range of impacts from solid waste. The figure represents a general concept; specifics of the eventual implementation are yet to be defined.

MACRO MATERIAL FLOW MODELING CONCEPTUAL STRUCTURE

The conceptual structure being adopted for the MMFM is based on the characteristics of the solid waste management system and the associated materials production and use cycles. Some of the characteristics of these systems are summarized here, in preparation for discussing the conceptual structure of the MMFM.

Traditionally, the materials production and use system and the associated solid waste management system have been viewed from a once-through perspective. Raw materials are harvested or extracted to provide feedstocks for production and manufacturing and also for energy production. The use of the products that are produced, as well as the production of energy, results in waste materials that are eventually disposed of into the environment. (Note that disposal can take the form of simply leaving the material out in the environment to eventually degrade and decompose, as many automobiles were deserted in the past; thus, disposal can be a lack of action rather than a specific conscious action.)

A more accurate and current representation of these systems, incorporating recovery and recycling of materials and energy from the waste, is shown in Figure 2. Materials recovery recycles material back into production and manufacturing for reuse. Energy recovery uses waste material to produce useful forms of energy, returning the resulting transformed wastes back into waste materials. Mining of materials from disposal sites to provide additional feed materials or to reclaim landfill capacity is also shown.[6,7]

The system shown in Figure 2 is the system that the MMFM is intended to model. The boxes in the figure represent material states, while the arrows represent processes that transform matter from one state to another. All of the processes are net energy users except those explicitly identified by the E+ symbol. The movement of materials through the system can be defined and calculated in terms of mathematical functions of such parameters as quantities and compositions of input material into a process, independent variables (e.g., economic and demographic measures), the operation of related processes, and previous outputs from the process under consideration.

Figure 2 is simplified somewhat for clarity. As an example, each of the processes in the figure produces relatively small amounts of waste subsidiary to the process. These have not been shown because their flows are more minor than those represented; however, they must be included in modeling the system to ensure the accuracy of the overall system representation.

Solid wastes are not produced uniformly throughout society and the economy, neither in quantity nor in content. Thus, it is useful to consider this model of materials production and use and the associated waste generation broken down by sectors (and, as necessary, subsectors) of the economy. Furthermore, wastes within a given sector vary widely. However, within a given sector, solid wastes produced are generally representative of the functions that generated them. This combination of sector and function can be used to define a matrix of solid waste origins, as shown in Figure 3.

The matrix shown in the figure is only representative of the eventual matrix that will be defined. It is expected that, based on information currently being collected on waste generation and the related functional drivers, the lists of both the prospective sectors and waste generating functions will be refined. However, such a matrix appears to be a valid mechanism to categorize and differentiate activities that can reasonably be expected to be predictable based on potentially available input information.

Taking into account the objectives of the MMFM, it will be useful to separately model each "cell" in the matrix in Figure 3. Results from the individual cells can then be accumulated as needed to cover the entire situation being considered.

To calculate the results for each cell, each of the processes in the materials production and use system and the associated solid waste system can be modeled in a relatively straightforward manner. Material enters the process and is transformed by the process into output material. Energy and other resource requirements are used by the process, and some inefficiencies inherent in the process result in a solid waste side-stream. To model such a process, the output of the process for a given time period must be defined as a function of:

- the input material
- a set of independent variables, such as gross national product, per capita income, population or population density, regulatory factors, and/or climate
- activity of related processes in other sector/functional waste type categories (i.e., other cells in the matrix) but not directly in the input or output chain of the process in question
- past outputs of the process.

This is illustrated in Figure 4.

For each of the major processes within the system, the results from each cell can then be aggregated across the matrix in Figure 3, as needed. The primary variables that would be aggregated across the matrix include the material quantities, timing, and compositions; energy input/output; and costs. Other impacts resulting from each process could then be derived from these primary variables.

STATUS OF MACRO MATERIAL FLOW MODEL IMPLEMENTATION

Efforts to implement the MMFM concept as described in this paper have only recently begun. The status of these activities is discussed below, with efforts to develop the necessary data and functional relationships discussed separately from the simulation modeling activities.

Data and Functional Relationships

Effective implementation of the MMFM concept will require a substantial amount of data on solid waste characteristics and origins, both to characterize the various solid waste streams and to develop the necessary mathematical representations of the functional relationships driving the processes in the system.

A preliminary review of available solid waste characterization data was performed as part of the initial concept development for the MMFM.[1] This review resulted in several observations relevant to the MMFM development effort.

Solid wastes are basically managed in two different ways. Collectively Managed Solid Wastes (CMSW), of which Municipal Solid Waste (MSW) is a good example, come predominantly from the Household/Residential and the Commercial sectors. Information on CMSW is fairly well available, because of past and current needs for accurate information to plan for this collective management. However, there are also a number of Independently Managed Solid Wastes (IMSW). These wastes, including a variety of industrial and agricultural wastes, come from much more diverse sources than do the CMSW. At the same time, accurate information on IMSW is generally harder to obtain (or, at least, the IMSW information is not as publicly available as that for CMSW). Thus, available data on solid wastes vary considerably depending on the current approach being used to manage the wastes.

CMSW, and more particularly MSW, has been the major focus of data collection efforts thus far, and these efforts have concentrated on the U.S. and Canada. This focus is largely in response to data availability. It is intended to eventually expand these efforts to encompass all types of solid wastes, throughout the world; this expansion is envisioned to take place in stages, as experience is gained in correlating the data and inferring the necessary functional relationships from it.

Even though data on CMSW are much more available than for IMSW, the available data are still somewhat sparse, coming generally only from communities that have performed studies to determine how to proceed on some aspect of their solid waste management program. In addition, these data are generally tuned specifically to the purpose of the study that was made.

Among the available data, there are considerable variations in per-capita amounts[8] and compositions of solid wastes. Also, because of the way much of the data is recorded, it is difficult to determine which functional waste types or origins account for what quantity and composition of waste. Thus, it will be challenging to generalize relationships corresponding to specific cells in the waste origins matrix from the available data.

Some studies have already been conducted to determine functional relationships similar to those needed to implement the MMFM concept.[9] The results of such studies will help provide some guidance for this effort.

The use of the waste origins matrix to break up the solid waste stream into its component parts is seen as a way of simplifying the functional relationships describing the processes involved. This should facilitate hypothesis, testing, and refinement of functional relationships to model each cell in the matrix. Initial efforts will be focused on selected areas of the matrix corresponding to particular areas of analytical interest.

Another possible option for deriving the necessary data and functional relationships from the body of available solid waste information is the use of adaptive modeling techniques, such as neural networks, to establish the relationships empirically. Neural networks are collections of simple inter-connected processing units that are capable, in theory, of mapping between any set of inputs and outputs. Neural networks have several features relevant to the problem of deciphering the solid waste information:

- Neural networks can model the temporal behavior of a system and can capture temporal dependencies in the data.
- Neural networks are capable of learning, and are easily upgraded through the incorporation of new data, thereby enabling the modeling network to be easily maintained in an up-to-date condition.

Neural networks have been successfully applied to the modeling of a variety of complex systems, including ecologies and economies, that exhibit large numbers of state variables, strongly non-linear relationships among variables, and functional relationships which vary over time. Because similar complexities are expected in the solid waste and associated materials production and use systems, neural networks may also work well for these latter systems. However, no efforts have yet been initiated to test the applicability of neural networks as part of the MMFM concept.

Finally, additional efforts being undertaken by various organizations are expected to provide an expanded base of solid waste data. Of particular interest, broader data on IMSW, including a global inventory of industrial wastes, will become available as a result of the Global Waste Survey that is to be completed by 1994.[10] Future efforts to record and develop solid waste data are also expected to obtain broader support as a result of such things as the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992.

Simulation Modeling

It is currently anticipated that the MMFM will be developed as a computerized logistics simulation model. Although the full details of the modeling structure have yet to be defined, some general decisions regarding model implementation have been reached.

Because of the potential level of complexity and detail in the eventual full implementation of the MMFM, and because of limitations on available resources, development of the MMFM is likely to take several years. It is impractical to delay analytical use until full implementation of the model is achieved. Therefore, the model will be implemented in stages, with each stage adding functionality.

To facilitate this stage-wise development, the model code will be modular. When improved algorithms or more detailed results are needed for a particular portion of the model, the applicable working module(s) can be replaced with an improved one that provides the enhanced functionality.

The simulation contained in the MMFM will be based on appropriate increments of time to obtain the necessary temporal resolution in the output results. Although the specific time increment to be used has not yet been defined, it is anticipated that to meet most of the purposes of the MMFM, a "time-slice" of one year should provide sufficient resolution. For many analyses, time-slices of five or even ten years may provide sufficient resolution, while substantially reducing the calculational load and the corresponding run-times of the model. The MMFM will be implemented to allow the time-slice to be adjusted as needed to meet the specific requirements of the analysis being undertaken.

Model coding and data development will be carried out in parallel. This will allow the two efforts to provide valuable input to each other as they progress, and will also minimize the total development cycle time. A set of example problems is being defined to guide and focus the early phases of the development. These example problems deal with only selected portions of the waste origins matrix and, thus, considerably reduce the complexity involved in the necessary data development and modeling efforts.

A major part of the current effort is the development of a simple, limited demonstration prototype model. This prototype will emulate major portions of the full MMFM functionality, to provide a basis for presenting and refining the MMFM concept, confirming the operability of the model and the usefulness of the results, and facilitating liaison activities with prospective users of the MMFM. The prototype will also provide valuable input to the determination of the particular techniques and software to be employed to develop the full implementation of the MMFM.

Because of the basic similarities between the MMFM concept and the materials flux simulation discussed in Reference 5, possible interaction and cooperation with the Society for Computer Simulation's Mission Earth activity is being investigated. In addition, the development of the MMFM is being carried out in collaboration with other PNL research efforts that have already developed and applied similar modeling techniques to predict broad-ranging impacts of human activities. This coordination allows a leveraged development of the methodology and tools to assess this type of problem area.

Model Validation

"For decision-aiding models, a model is useful only when the decision maker believes (rightly or wrongly) that it is valid."[11]

The purpose of model validation is to confirm that the model is realistic (i.e., produces results that reflect the real world to a reasonable degree). It is particularly important to determine that the model provides reasonable comparisons of alternative scenarios, because models such as the MMFM are more often used for such comparisons than for stand-alone predictions of future conditions.

Models such as the MMFM that are based on assumptions about the future are difficult to validate. It will be necessary to compare model output for appropriate cases with historical data, where such relevant data exist. Where data do not exist to corroborate the results of the model, the validation will have to rest more on the following considerations:[12]

- face validity, which is a measure of the general credibility of the model's realism
- variable or parameter validity, which is a measure of the ability of the model to interpret variations in input parameters.

Because the MMFM will be developed modularly, with increasing breadth and depth of detail being added, validation of the MMFM will need to be carried out continuously, in parallel with model development.

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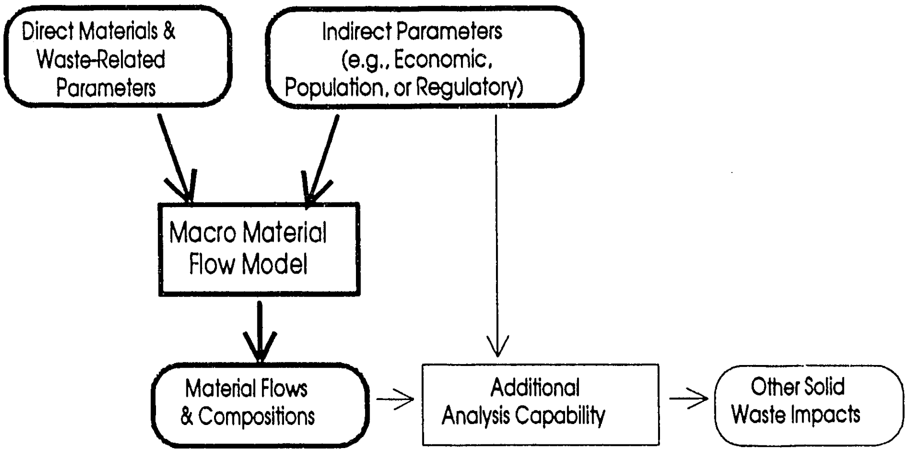

Figure 1. Use of Macro Material Flow Model for evaluating solid waste impacts.

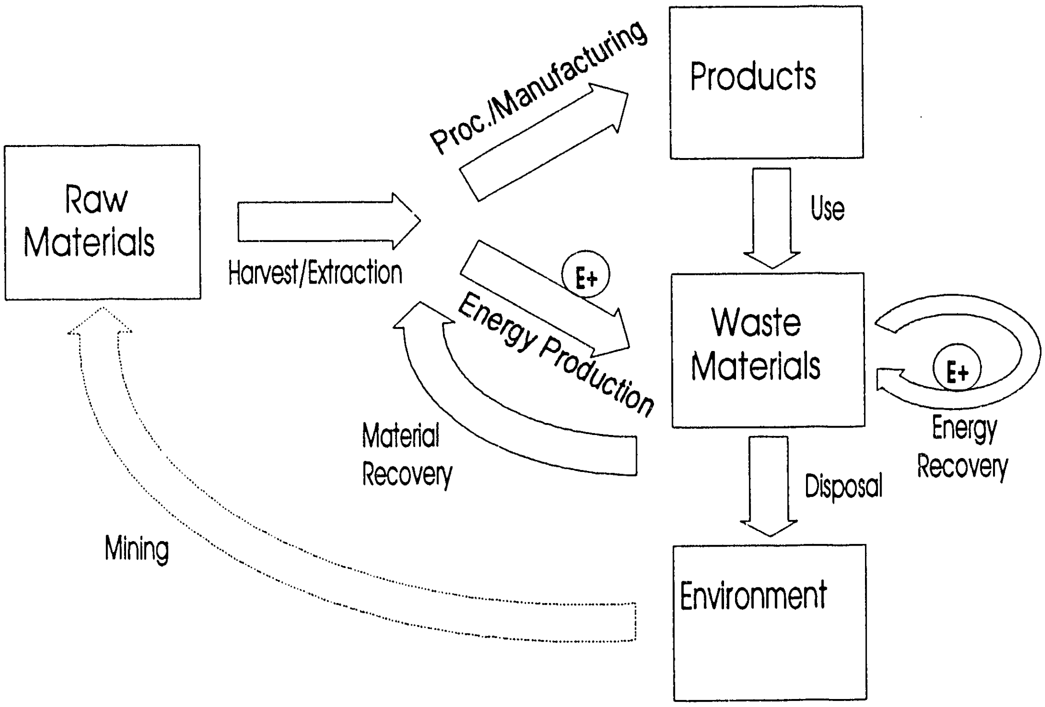

Figure 2. Materials production and use cycle, including solid waste management.

Functional Waste Types	Household/Res.	Industrial	Commercial	Energy	Construction	Ag./Forestry	Medical	Government	Transportation	Mining
Packaging										
Conversion Loss/Scrap										
Used/Failed/Defective										
Processing Residuals										
Debris										
Food Waste										
Yard Waste										
General Trash										

Figure 3. Matrix of solid waste origins.

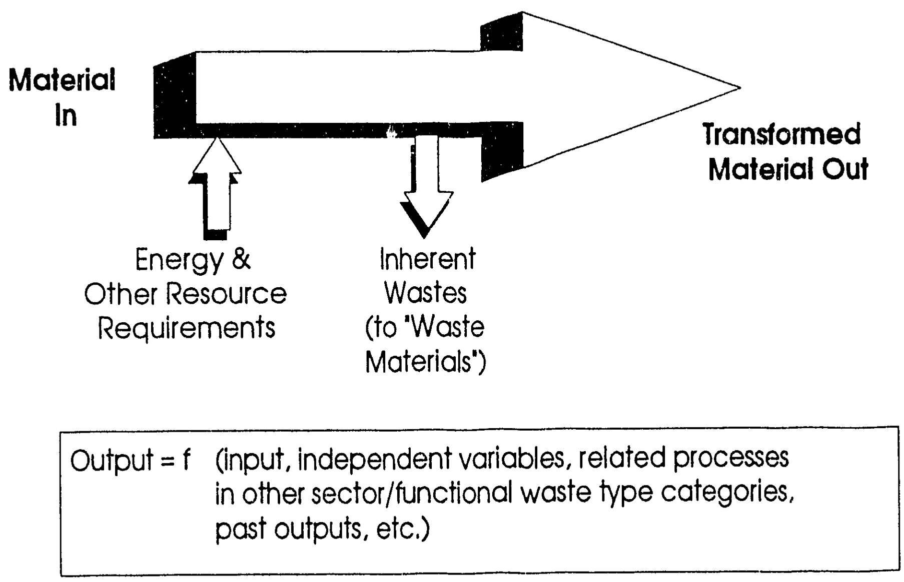

Figure 4. Simplified model of a process in the MMFM system.

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