An Overview of the Global Systems Simulator

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The Global Systems Simulator (GSS) is a simulation model intended to illustrate some of the implications of the concept of sustainable development as it is applied to human ecology at the global scale. In particular, GSS is a decision support tool for performing 'lookahead' analysis. It provides the means by which human society can perceive the longer term consequences of collective societal actions before those actions are taken and to decide upon appropriate courses of action in the light of knowledge of the their consequences. A GSS tutorial showing how to navigate and build scenarios is available.

The GSS provides a relatively simple example of an application of some of the modelling concepts and methods developed by *whatIf?* Technologies called the design approach to socio-economic modelling; it also serves to demonstrate how a simulation framework can be realized using the whatIf? ® software tools developed by *whatIf?* Technologies.

The Concept of Sustainability

Sustainability is a property of a socio-economic system in the context of its physical environment. It is a property that applies to a system as whole. Just as 'temperature' and 'pressure' are properties that apply to a gas, not to the individual molecules that constitute the gas, sustainability is a property of the global ecosystem, not its constituent processes. Consequently sustainability can only be understood within the context of a theory or conceptual framework that represents the main elements of the entire system. The difficulty arises because the socio-economic system to which we wish to apply the concept of sustainability is characterized by complexity. Its constituent elements are human activities and naturally occurring environmental processes; each process has its own time dynamic and is linked by means of a network of flows of materials and energy; furthermore aggregation over space and time tends to obscure the relationships among the components of the system. It is obvious that a reductionist approach to the problem is a contradiction; yet representing the component processes of the entire system is made difficult because the conventional analytical tools of the social sciences are not powerful enough to approach a problem of this magnitude. Also, in many instances, the physical sciences have not developed a full understanding of the underlying ecological processes and their interrelationships with the consequence that risk and uncertainty must be faced directly.

Sustainability is a dynamic concept; it applies to the trajectory of a system. In order to determine whether a socio-economic system has the property of sustainability, it is necessary to examine its future evolution path. However, what the future evolution path will be is in part the result of human activities that are subject to choice. Therefore, it is necessary to examine possible evolution paths that are contingent upon societal choices. It is possible that only a subset of the evolution paths have the property of sustainability. (Hopefully the subset is not null.) From this discussion, it follows that the objective the exercise is to determine what choices must be made in order to yield the system sustainable.

Accordingly, the strategy adopted for the GSS is to examine the property of sustainability in the context of an entire socio-economic system, but one whose components have been reduced to the minimum number required to illustrate environment/economy linkages. Conceptual clarity is gained, if indeed it is achieved, at the cost of numerical accuracy. However, the concepts and methods presented in this paper are capable of handling the compositional detail and the complexity of the relationships that would be required to improve quantitative accuracy to a more acceptable degree.

The Design Approach to Socio-Economic Decision Analysis

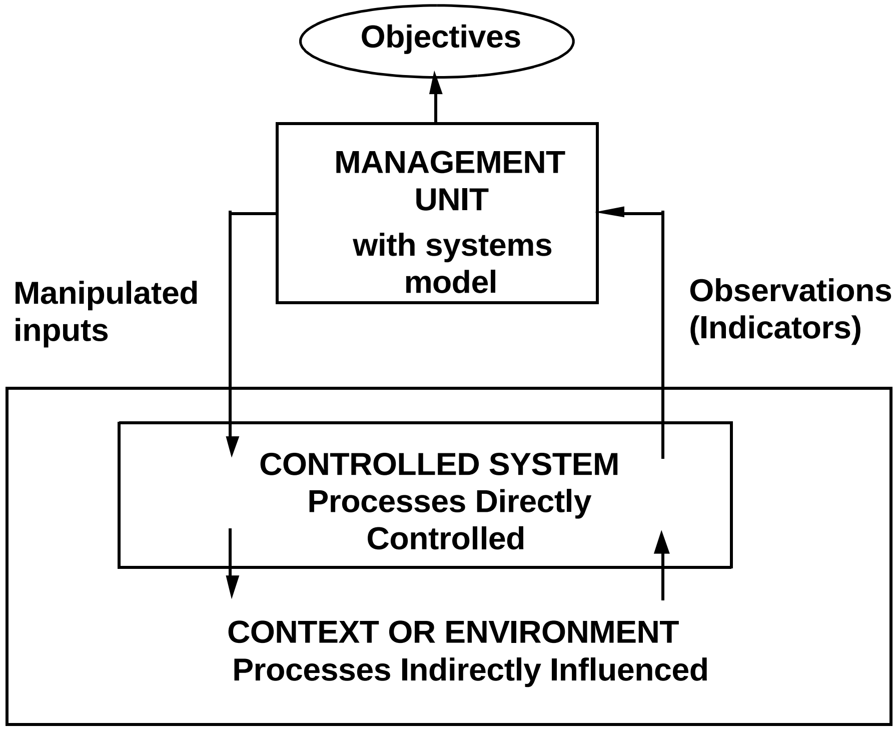
The design approach applies concepts from general system theory and control theory to socio-economic decision analysis. Effective action arises from a decision process that has three necessary ingredients: a well-defined objective, an understanding of how the system in question works, including how it interacts with its environment, and continuing observations of the state of the system that provide feedback to the system manager.

The understanding, which is in fact a model of the system - a systems model, plays a pivotal role in the decision process. It serves to identify the set of state variables or indicators to be observed or monitored and relates the observed state variables to the objective, in this way providing feedback to the decision making process. The systems model also supports the choice of objectives by facilitating the definition and exploration of alternatives.

In this context, it is worth recalling the cybernetic theorem, the Law of Requisite Variety, which states that the regulation that the regulator can achieve is only as good as the model of the reality that it contains [Ashby, 1956].

> *It comes down to this: we cannot regulate our interaction with any aspect of reality that our model of reality does not include - whether as to its theoretical range or as to its observational facilities and resolution - because we cannot by definition be conscious of it* [Beer, 1980].

In the application of this framework to the achievement of the objective of sustainability the 'manager' or controller is society itself: individuals and the institutions of society that have been delegated responsibility for managing various aspects of human activities. Since this 'manager' system is obviously not monolithic, effective action will depend upon managers having a common understanding or shared systems model.



In the absence of widely shared understanding or common systems model, the feedback loop from observations of the system to the system manager is weak. The property of sustainability cannot be directly observed or monitored because it is a property that applies to the future of the system and the future of the system is not fully determined or indicated by its present state.

From the discussion above, it is clear that a conscious and explicit systems model plays a crucial role in developing and communicating a common understanding needed for effective interpretation of the observations and for both individual and collective action. The GSS is a first attempt to make such a systems model explicit.

Features of the Design Approach

- **The User/Society as an Integral Part of the System**
  The systems model consists of two components: an open simulation framework that represents the processes of the system to be managed with their context and the user/society, which is the source of novelty or learning. Through interaction with the framework, the user/society explores the implications of decisions and changes in the environment. Exploration is a learning process that enables the user/society to increase his understanding of the system. In this way learning from experience can be incorporated into the framework.

- **The Concepts of System, Process, Dynamics**
  A simulation framework is a representation of the processes that constitute a system. The systems of concern for the issues of global sustainability are human activities and the naturally occurring biological and geological processes that sustain human populations. A fundamental concept of systems theory is that

  > *(The concept of) process is primary . . . every structure we observe is a manifestation of an underlying process.* [Capra, 1985]

  'Process' is a dynamic concept concerned with the transformation of input streams into output streams within an arbitrary system boundary. The properties of the system as whole, such as sustainability, emerge from the interactions among the constituent processes and are not simply the properties of the component parts. The representation of time structure is essential.

  > *Interactions among component processes take the form of causal chains that may be complex. When sequences of cause and effect become circular, then the mapping of those sequences onto timeless logic becomes self-contradictory or paradoxical.* [Bateson, 1980]

- **Stocks and Flows**

  > *Another taxonomic and conceptual problem that has plagued economics from the time of Adam Smith is the confusion between stocks and flows . . . The capital stock is a population of items, production is births into that population, consumption is deaths . . . Furthermore , the idea that production is consumption is only partly true. What we get satisfaction from for the most part is use, not consumption . . . This has led to . . . the absurd view that it is income which is the only measure of riches.* [Boulding, 1978]

- **Disequilibrium and Tension**
  The simulation framework is designed in such a way that the system of feedbacks among the processes represented in the framework is incomplete. To the extent that the feedback mechanisms are incomplete, the possibility of discord or disequilibrium among the constituent processes arises. This discord creates tension in the mind of the actor or framework user that invites a creative response. It is this idea of tension arising from disequilibrium that makes the user of the framework an integral part of the model.

  > *Equilibrium has become a kind of holy sacrament in economics and has seriously diverted attention from the real world of Heraclitean flux . . . The economic system is a structure in space-time. Consequently, it is evolutionary, subject to constant and irreversible change.* [Boulding, 1988]

The Structure of the Global Systems Simulator

The GSS represents the physical substrate of the global socio-economy that consists of sixteen processes: population growth, two consumption processes, two goods production processes, recycling, pollution treatment, energy production from renewable and non-renewable sources, natural resource production from forestry, agriculture, and mining, and a research process that transforms effort into capital-, energy-, or labour-saving technology. Energy, raw materials, finished goods, waste materials, pollutants, human effort, and technology embodied in plants, are the flows that link the various processes. The global socio-economy has an endowment of natural resources, a human population, and a stock of artifacts that embody accumulated know-how. Table 1 lists the processes that constitute the socio-economy, the stocks and associated with the various processes and the flows that cross various process boundaries.

Table 2 shows the output flows, input flows, and stocks associated with each process. Those flows in italics are implicit and are not represented by variables in the model. The indexes in parentheses associated with stocks indicate the categories into which the stock is subdivided. All stocks and flows are measured in each time period and carry the index 't'. The index 'a' indicates age in single years, 's' sex, 'ac' age classes associated with workers, 'q' land quality of which there are three classes: high yield, medium yield and low yield, and 'f' factor of which there are three: labour, energy, and capital.

The GSS represents a population of people, stratified by age and sex. Population growth is governed by fertility, the number of children produced by each female, and mortality, the probability that each individual will die as a function of age and sex. The population requires nutrition and services, such as shelter. Nutrition is obtained through the consumption of food. Services are supplied from a stock of durable goods that may be thought of as houses, hospitals, schools and other infrastructure. The provision of services requires not only a stock of durables, but, as well, energy and labour services, for example, doctors, nurses, orderlies, teachers.

Durables are made from ‘bricks’, as are all factories or plants and hydro dams. Bricks are composed of a combination of wood and metal. They are manufactured in plants that are themselves made of bricks. The brick manufacturing process requires labour and energy as well as the materials, wood and metal, from which the bricks are fabricated. The fact that brick plants are themselves made of bricks gives rise to a cycle that reflects the useful life of brick plants. Food is manufactured in plants from crops in a process requiring both labour service and energy.

The natural resource base provides the raw materials and energy required to sustain the population. Crops are produced on agricultural land; they require energy and labour service for planting and harvesting. Crop yields depend upon the quality of the land, the amount of pollution emitted into the atmosphere, and the amount of fertilizer (measured in energy units) applied to the land. The agriculture model is designed in such a way that high yield land is used before secondary and tertiary land.

Wood comes from trees which are grown on forestland. Unlike crops that reach maturity and may be harvested in a single time period, trees grow over a multi-year period. Trees add volume each year as a function of their age and each tree requires forestland, again as a function of age. Trees are subject to natural mortality; in early years mortality is due to crowding and mortality is sufficient to provide the forest land required by the survivors; in later years after trees have reached full maturity natural mortality increases so that the maximum tree age is 100 years. Natural mortality is an increasing function of pollution accumulated in the environment. Trees may of course be harvested for their wood; harvesting requires both energy and labour service. Natural regeneration is sufficient to offset natural mortality. Planting may enhance forests regeneration, a process requiring both energy and labour service.

Metal is the product of mining and ore concentration activities. Mining requires energy and labour service, whereas ore concentration requires energy; however the quantity of energy per unit metal recovered increases as a function of accumulated ore production. The idea here is that the highest quality ores are mined first.

There are both renewable and non-renewable sources of energy. Energy is available from four sources: hydro facilities, solar and nuclear facilities, fuelwood, and non-renewable fossils consisting of oil, gas and coal. Hydro dams and solar and nuclear facilities are constructed of bricks. Once a dam is in place there is a stream of energy in every subsequent time period; however, the number of bricks per unit generation capacity increases as a function of the installed capacity. Solar and nuclear facilities require a fixed number of bricks per unit capacity; however, unlike hydro dams, solar and nuclear facilities wear out according to a life table and must be replaced. There are fixed resources of oil, gas and coal that must be explored before they can be produced; exploration effort requires labour services; the additions to reserves per unit exploration effort diminishes as the resource limit is approached. Of course, once the resource has been fully explored further exploration effort will yield no additions to reserves. Production of fossil energy requires both energy and labour service.

GSS includes a materials recycling process. The stocks that are made of bricks, including the stock of durables, food plants, brick plants, recycling plants, and pollution treatment facilities, wear out and must be replaced according to life tables. The metal in the bricks that are discarded as these facilities wear out may be recovered in recycling plants. Bricks are recycled to the extent that there has been investment in recycling plants. The operation of the recycling plants requires energy and labour service; however, the amount of energy per unit recovered metal increases as the fraction of metal recovered increases.

Pollutant wastes are generated in the processes associated with the use of durables stocks and with brick and food production. If the pollutant is allowed to enter the environment untreated, as noted above, agriculture yields and forest mortality are affected. Pollution may be rendered environmentally benign if it is processed in pollution treatment facilities. Pollution treatment is an 'end-of-pipe' process that requires only the installation of the pollution treatment equipment that is composed of bricks. As with recycling, pollutant wastes will be treated to the extent that capacity has been put in place. Untreated pollution accumulates in the environment.

Technological change is an important feature of GSS. A research process is represented in the framework that serves to effect factor substitutions and changes in factor efficiency. The factors of production are labour service, energy and capital. Use of these factors in various processes are reflected by coefficients indicating labour service and energy per unit activity; for those processes involving capital in the form of stocks of durables or plants, capital efficiency is indicated by coefficients indicating bricks per unit capacity. A factor substitution possibilities surface is defined such that energy and capital may be substituted for labour. For secondary processes - those involving capital stocks or plants, (durables use, food and brick production and recycling) the position on the factor substitution surface is associated with the plant in the year in which it was built. For primary processes - those requiring labour and energy, but not capital, (agriculture, fossil energy production, forest harvesting and planting), a position on the surface may be associated with each year. Research effort may be devoted to energy and capital saving research. Factors that modify the energy and capital efficiency coefficients are a function of the accumulated research. These coefficients are associated with the plant or stock in the year that the plant is built and are fixed through the life of the plant. Consequently, the penetration of new technology in the secondary processes depends on the rate of turnover of capital stock, which in turn depends on the stock life tables, and the change in demand for the stock. For primary processes the factor efficiency coefficients are a function of accumulated energy saving research in each time period. In these sectors, changes in factor efficiency are immediately imbedded in the processes.

The time horizon of the simulation period is set at one hundred years. This time horizon is sufficiently long for all of the stocks in the system to have turned over at least twice. This means that the future of the system is relatively independent from its initial conditions. The time step of the calculations is one year. The dynamic properties of this framework are very rich since it involves a number of stocks with different lives. Of particular interest in this respect is the penetration of new technology into the stocks of productive capacity.

The GSS consists of twenty-one calculators or independently executable sub-models that represent the sixteen processes of the underlying socio-economy. These calculators are arranged in a conceptual hierarchy, shown in Figure F-i. The framework distinguishes six components:

1 the **Demography** component that keeps track of population growth and the availability of labour services from the population.

2 the **Consumption** component that keeps track of the material standard of living of the population in terms of consumable goods per capita and of the stock of artifacts or facilities per capita;

3 the **Infrastructure** component that registers decisions to invest in facilities to treat pollution, to recycle waste, and to produce energy from renewable sources and the decision to devote effort to performing research; these investments will, in the future, make the society more productive and efficient in terms of the use of both human and natural resources;

4 the **Materials Transformation** component that represents the transformation of raw materials and energy into finished goods and the operation of processes that treat pollutants and recycle waste materials, and;

5 the **Natural Resources** component that represents the harvesting and husbanding of renewable resources and the extraction of non-renewable resources.

6 the **Indicators** component that performs the housekeeping tasks of consolidating information from the other components for the purpose of calculating indicators of the state of the system

The dependency structure of the GSS is shown in Figure F-ii. This diagram shows the flows of information among the eighteen calculators that represent the real or non-housekeeping processes of the simulator. The dependency structure of the GSS was designed to highlight four tensions, shown in Figure F-iii.

- **Labour tension:** The simulator does not resolve differences between the availability of and requirements for labour services. The availability of labour depends upon population levels; requirements for labour depend upon the level of activity in the various sectors and the technology deployed in each sector. Consequently, scenarios may be created that are not feasible because more labour is required than is available. Scenarios with an excess of available labour over requirements are feasible but may be undesirable.

- **Agriculture Crop Tension:** Again, the simulator does not resolve differences between the availability crops and the requirements for crops. Availability is limited by the quantity of land devoted to agriculture and the yields which depend upon a number of factors such as the intensity of fertilizer use, the genetic yield factor, and untreated pollutants. Scenarios characterized by high population growth, high consumption per capita, and low pollution treatment may not be feasible because of excess of requirements for crops over availability.

- **Wood Tension:** There is a tension between the availability of wood and requirements for it. As with crops, availability of wood is limited by the quantity of land devoted to forestry, but more importantly by the rate of growth of trees and the rate of reforestation. Scenarios characterized by high levels of investment in facilities made from durable goods, low forest management activities, and low levels of pollution treatment may not be feasible because the forest cannot sustain the required harvest.

- **Energy Tension:** Ultimately energy supply is limited by endowment of fossil resources and the rate at which renewable resources are available. In the short run energy supply may be limited to the extent that not sufficient effort has made devoted to exploration with the consequence that reserves are depleted or to the extent that there has been insufficient investment in facilities for capturing renewable energy. Thus scenarios may be created where the requirements for energy outstrip energy supply.

It is the responsibility of the model user to explore the combinations of control variable settings that result in scenarios that are feasible and that have the property of sustainability. The future trajectories of this socio-economic system reflect different sets of decisions or choices that can be made about human activities. The major choices that can be examined using the GSS are choices concerning population growth, the material well-being of the population, land use, and the degree to which the society invests in the capacity to produce renewable energy, to recycle waste materials, to treat pollutants, to develop and deploy technology, or to manage the forests. The major control variables are listed in Table 3.

Calculator Structure and Descriptions

The structure of each calculator is elaborated by a diagram that can be seen in the GSS tutorial. Each diagram is labelled (for example Population) and information about that calculator may be obtained by right mouse clicking on the label and selecting Show Info and then expanding the notes field. English language descriptions are layed out here. The calculator diagrams make use of symbols that represent information or variables that are the inputs and outputs of a calculation. Variables are represented by symbols: the barrel symbol represents a stock; the pipe represents a flow, and; the hexagon a parameter or ratio variable. Procedures, represented by rectangles, contain the equations or algorithms for transforming the values of input variables into values of output variables. The arrows connecting variables to procedures indicate whether the variable is an input or output of the procedure. The flow of information among components is indicated by the small rectangles containing the numbers of the components to which or from which the variable is linked. The indexes contained in the square brackets indicate the extent of the information in the variables. For example, the index 't' indicates that the information is broken down by time.

Calibration

The 18 calculators of the framework requiring calibration have been calibrated over the period, (1950- 2004) with the result that there is a complete and consistent set of historical values for all of the variables in the framework. The calibration is based on data for the globe, including population, land use and energy production. The calibration might be described as impressionistic in the sense that the overall magnitudes are in the right ballpark, but it must be emphasized that a great deal more effort would be required to understand and exploit additional data.

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Tables and Figures

Table 1: Processes , Stocks and Flows

	Processes		Stocks		Flows
1	Population	1	People	1	Wood
2	Food Consumption	2	Workers	2	Energy
3	Durables Use	3	Durables	3	Crops
4	Food Production	4	Food plants	4	Ore
5	Brick Production	5	Brick plants	5	Metal
6	Pollution Treatment	6	Pollution Treatment Capacity	6	Bricks
7	Materials Recycling	7	Recycling plants	7	Food
8	Agriculture	8	Hydro Dams	8	Labour Service
9	Ore Concentration	9	Solar and Nuclear Capac-ity	9	Pollutant
10	Mining	10	Agriculture Land	10	Technology
11	Forestry	11	Forest Land	11	Waste
12	Hydro Production	12	Other Land	12	Research
12	Solar and Nuclear Produc-tion	13	Trees		
14	Fossil Exploration	14	Accumulated Research		
15	Fossil Energy Production	15	Accumulated Pollution		
16	Research	16	Fossil Reserves		
		17	Fossil Resources		

Table 2: Relationships Among Stocks, Flows and Processes

	Processes	Output Flows	Input Flows	Stocks
1	Population	Labour Service	*Nutrition* *Services*	People [a,s] Workers[s,ac]
2	Food Consumption	*Nutrition*	Food	
3	Durables Use	*Services* Waste	Bricks Labour Service Energy Technology	Durables [a]
4	Food Production	Food Waste	Crops Bricks Labour Service Energy Technology	Food plants [a]
5	Brick Production	Wood Metal Waste	Bricks Labour Service Energy Technology	Brick plants [a]
6	Pollution Treatment	Net Pollutants	Gross Pollutants Bricks	Pollution Treatment Capacity [a] Accumulated Pollution
7	Materials Recycling	Metal	Waste Labour Service Energy Bricks	
8	Agriculture	Crops	Labour Service Energy Technology	Agriculture Land [q]
9	Ore Concentration	Metal	Ore Energy	
10	Mining	Ore	Labour Service Energy Technology	
11	Forestry	Wood	Labour Service Energy Technology	Forest Land Trees [a]
12	Hydro Production	Energy	Bricks	Hydro Dams
13	Solar and Nuclear Production	Energy Waste	Bricks	Solar and Nuclear Facilities
14	Fossil Exploration		Labour Service	Fossil Reserves[ff] Fossil Resources[ff]
15	Fossil Energy Production	Energy	Labour Service Energy Technology	
16	Research	Technology	Labour Service	Accumulated Research [f]

Table 3: Major Control Variables

Variable	Index	Calculator	Role
'total period fertility' 'mortality'	t s,t,a	Population	controls the birthrate and death rate and together control population growth
'participation rates' 'work hours per week' 'work weeks per year'	s,ac,t t t	Available Labour	control the availability of labour relative to the population
'food consumption per capita'	t t	Food Consump-tion	control the material standard of living of the society
'durables per capita'		Durable Use	control the material standard of living of the society
'labour intensity coefficients' 'energy saving research" 'capital saving research'	t t t	Technology	controls the position on the factor substitution surface controls the effort devoted to energy saving research controls the effort devoted to capital saving research
'planned (recycle) plants	t	Recycle Capacity	controls societal investment in recycling plants
'planned (pollution treatment) plants'	t	Pollution Treatment Capacity	controls societal investment in pollution treat-ment plants
'planned (hydro) plants'	t	Hydro Capacity	controls societal investment in hydro plants
'planned solar and nuclear plants'	t	Solar and Nuclear Capacity	controls societal investment in solar and nuclear plants
'recovery fraction'	t	Recycling	controls share of metal to be recovered
'energy from wood'	t	Forestry	controls volume of wood to be used as an energy source
'harvest share'	flt,t	Forestry	controls wood harvest distribution
'exploration effort'	t, ff	Energy Pro-duction	controls the amount of effort (labour service) invested in exploration to add to reserves of oil, gas and coal
'land transfers'	ltc,t	Land Accounts	controls transfers of land among forestry, agri-culture, and non-productive

Figure 1: Hierarchy

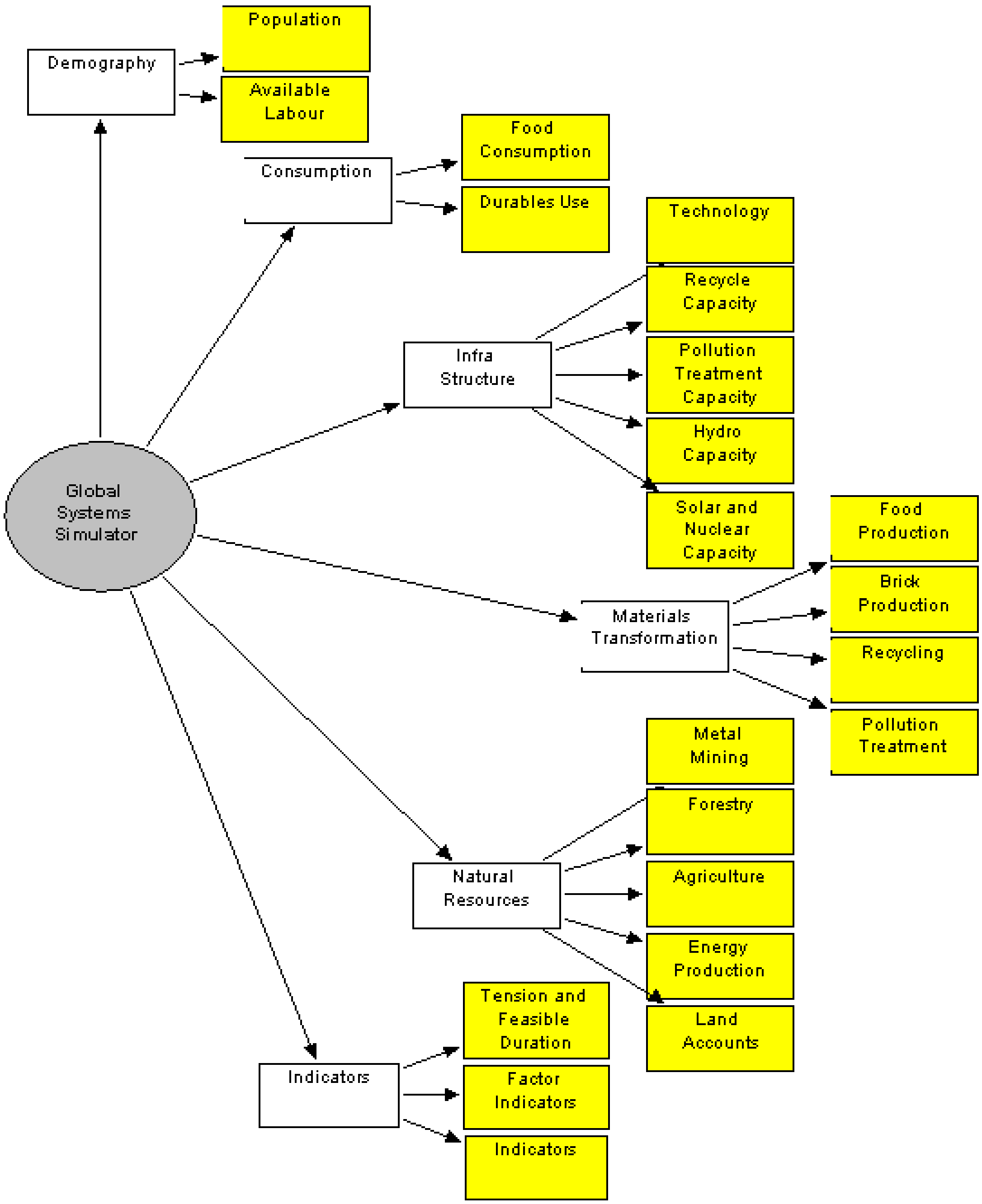

Figure 2: Dependency Structure

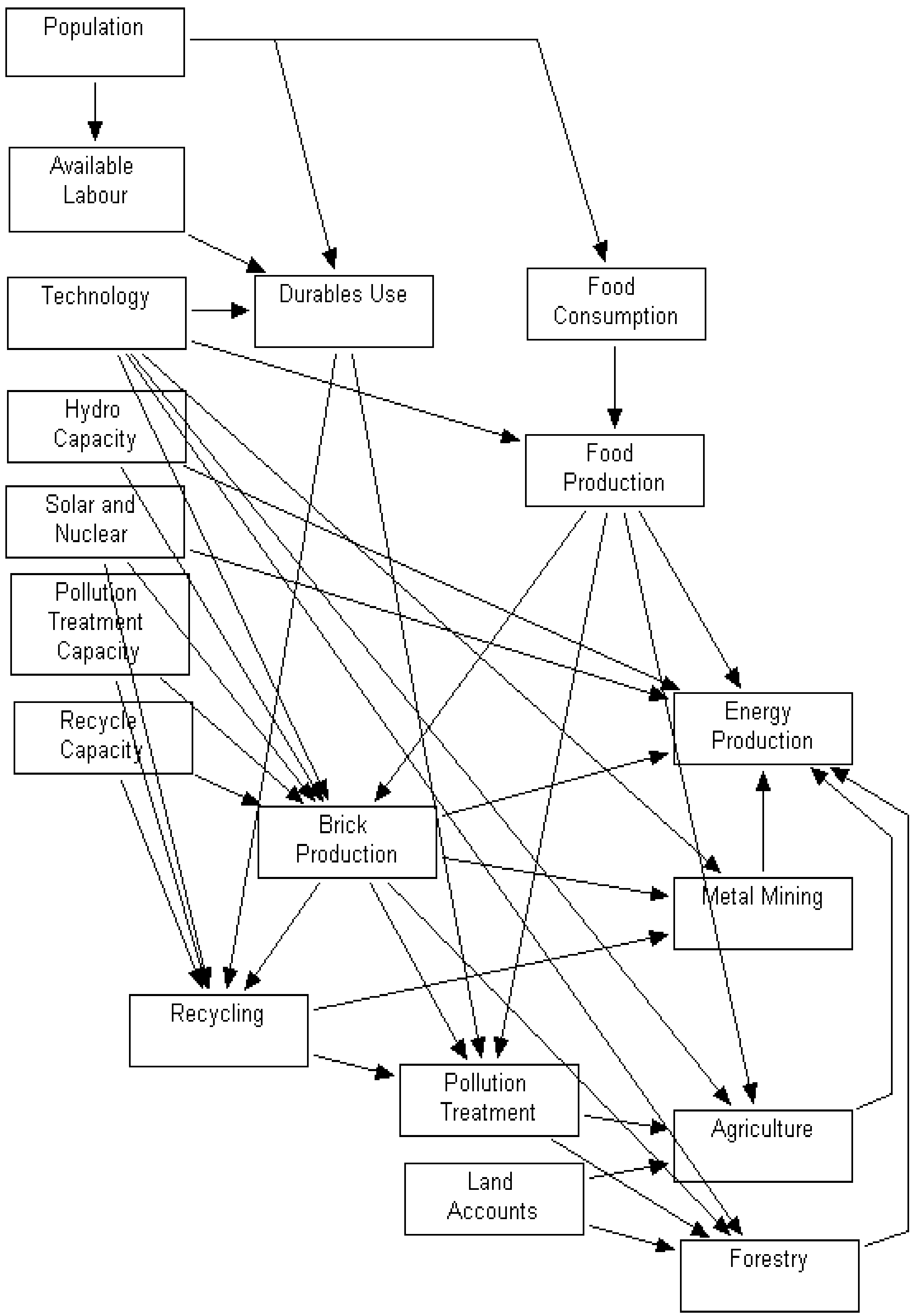

Figure 3: Tensions