A System Dynamics Modeling Framework for Sustainable Manufacturing

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ABSTRACT

This paper proposes a framework for application of system dynamics modeling to sustainable manufacturing. Sustainable manufacturing involves interaction of multiple complex systems including those in manufacturing, environmental, financial, and social domains. A concerted effort involving a number of researchers may be required to develop the requisite capability to model sustainable manufacturing with a flexible scope. At present, it is difficult for researchers to collaborate, share, and reuse models and components due to lack of consistency in several aspects including taxonomy and modeling approaches. The proposed framework is a first step to move towards composability of sustainable manufacturing model components developed by different research teams. The proposed framework organizes the major factors influencing sustainable manufacturing into four interacting complex domains. The framework is intended for use as a platform to develop model components that may be integrated to analyze sustainable manufacturing for different industries and geographies.

1. INTRODUCTION

Modern manufacturing consumes large amounts of resources, generates waste, and pollutes the natural environment. Some of the raw materials and energy resources consumed are non-renewable and often, toxic pollution is vented off into the atmosphere and waste is disposed of indiscriminately. This practice has resulted in adverse environmental problems such as acid rain, poisoning of the biosphere, global warming, climatic change, and a concern about depleted natural resources. So, a question has been asked as to whether continued industrial expansion and manufacturing production in the current manner would be sustainable in the long term. Some authors have concluded that global ecological constraints related to resource use and emissions would impose a limit to manufacturing and economic growth sometime during the twenty-first century (Meadows et al. 1972). The term sustainable development has been coined. The Brundtland Commission defined sustainable development in 1987 as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environment and Development 1987). Sustainable manufacturing refers to developing and practicing technologies to transform materials into finished products with reduction in each of; energy consumption, emission of greenhouse gases, generation of waste, use of non-renewable or toxic materials (Madu 2001). While practicing environmentally friendly manufacturing, the business must remain economically viable and socially beneficial. Hence, the Triple Bottom Line (TBL), i.e., people, planet, and profit for assessing a Company's performance. Sustainable development is often analyzed by considering the three elements: social sustainability, environmental sustainability, and financial sustainability. In this paper, we also add manufacturing sustainability.

1.1. Role of regulations on sustainable manufacturing

To achieve sustainability many countries have enacted environmental legislation that restricts resource consumption, pollution levels, and waste disposal; and encourages uses of recyclable materials. Such legislation often imposes minimum recyclable materials, CO_2 and other green house gases (GHG) emission, and the disposal of waste and manufacturing byproducts. An example is the Waste Electrical and Electronic Standard of the European Union (European Commission on Environment 2009).

Even though the U.S. environmental performance has lagged behind that of many other industrialized countries in recent times, a National Environmental Policy Act has been in place since 1969. This Act declared as its goal, a national policy to create and maintain conditions under which humans and nature can exist in productive harmony, and fulfill the social, economic, and other requirements of present and future generations of Americans (U.S. EPA 2009). The Act led to the creation of the Environmental Protection Agency (EPA). The agency is the government's watch dog to ensure that companies and organizations adhere to environmental law. A number of Acts have been enacted including the Clean Air Act, Clean Water Act, Safe Drinking Water Act, Resource Conservation and Recovery Act, Toxic Substances Act, Federal Insecticide, Fungicide, and Rodenticide Act, and the Emergency Planning and Community Right-to-Know Act (U.S. EPA 2009). EPA achieves environmental compliance by enforcing the law and assessing and imposing fines for non-compliance.

Various approaches have been used by authorities to classify environmental policy procedures, which determine the incentives (or fines) used to achieve compliance with environmental safety requirements. In turn, the same policies are responsible for defining training requirements for industries. According to the United Nations Environmental Protection (UNEP) agency (UNEP 2009) there are three categories of instruments:

- *Regulatory instruments* that mandate specific behavior: In Organization for Economic Co-operation and Development (OECD) countries regulatory instruments are the foundation on which environmental quality has been built. These countries have relied on specified compliance. However, the above method has the tendency of making the regulated community feel alienated, and tends to oppose the rule-makers. Regulated companies have tended to use end-of-pipe technologies. In contrast "shared responsibility" for negotiated compliance enhances better exchange of information among all stakeholders.
- *Market-based instruments* that act as incentives for particular activities: These incorporate the firm's polluting activities into taxes, fees, and charges. Alternatively, incentives are also used to promote cleaner production activities.
- *Information-based instruments* see to change behavior through the provision of certain information: This can be used in addition to regulatory and financial approaches. The objective here is to build capacity within industry, for example, through publication and dissemination of relevant case studies.

Today, with increasing awareness for environmental protection, many consumers prefer "green" products. The associated goodwill of companies that practice sustainable manufacturing could improve market prospects for their products. Hence, in response to environmental regulations, awareness, and in some cases consumer and community pressures, companies have started to assert sustainability as one of their strategic priorities.

A good example is the automotive industry. With increasing awareness of the effect of automotive manufacturing and the automobile use on the environment as well as dwindling fossil fuels, the industry is shifting to sustainability. Some of the relevant initiatives are:

- Designing a car so that it is made up of recyclable materials (from cradle-to-cradle concept), while improving its reliability and service life.
- Increasing efforts in automobile research and development of energy efficient cars, e.g., hybrids.
- Reducing use of energy during production. For example, switching off machines when not in actual production or application of energy efficient technology.
- Reducing usage of hazardous materials during production.
- Handling and disposing well whatever waste is produced (the policy is to reduce this waste to a minimum).

As a consequence of these efforts, significant improvements have been made in the automobile industry. In Japan, for example, the following have been achieved (JAMA 2007):

- Greater reduction in CO_2 and volatile organic compounds emissions and waste matter in plant operations.
- Improvements in materials used in manufacturing to increase end-of-life recycling. Currently, up to 75% (mostly metals) of automotive shredder residue is reused.
- Fuel economy where new fuel-efficient cars now reach 16km/liter (39 miles/gallon).
- Passenger cars certified as low emission cars now constitute 95% of all cars manufactured.
- Great reduction in use of hazardous materials and substances.

Similar studies have been reported in the United Kingdom where for example, the energy used to make each car fell from 4.3MWh/unit in 2001 to 2.5MWh/unit in 2006 and the water used per vehicle reduced from 6.2 m^3 to 3.3 m^3 during the same period (Auto Industry 2007).

1.2. Current practice of modeling manufacturing systems

The primary reason for building simulation models is to provide support tools that aid the manufacturing decision-making process. Typically, discrete event simulation is done as a case study commissioned by manufacturing management to address a particular set of problems. Studies often model some aspect of current operations and predict the effect of some hypothetical change(s) to those operations. The performance of current and proposed systems is evaluated according to some set of metrics. If the simulation validates that sufficient improvements can be expected, then the proposed changes are implemented. However, discrete event simulation in manufacturing seldom addresses sustainability issues.

Discrete event simulation of "what if" analyses still essentially focuses on streamlining and validating processes, reducing costs, and meeting schedules; not the identification and evaluation of environmentally friendly alternatives. Occupational safety and health considerations may not be accounted for in process models. Recovery, recycling, and life cycle costs (LCC) of materials are often not addressed in design and manufacturing simulations. Simulations usually do not deal with the usage and disposal practices of product users after sale. These issues are not modeled today because of the way the manufacturing simulation systems were developed and evolved. These systems were modeled to help a company to meet design and production objectives while sustainability constructs within the systems were left out. In addition, modeling sustainable manufacturing has been fraught with problems such as inconsistent terminology, variation in modeling methods, level of abstraction, unavailability of data, and complexity of modeling systems of systems. However, as a consequence of interest in sustainability, firms are increasing efforts to build models to optimize their operations incorporating social and environmental impacts.

1.3. Incorporating sustainability concepts in models of manufacturing systems

Many of the sustainability factors mentioned in the previous subsection do interact, influencing, restricting, and depending on each other. For example, reducing waste by adopting new technology or using "clean" and easily recyclable raw materials and inputs may increase manufacturing cost at the beginning but reduce fines and reduce material costs in the long run when materials in used products are eventually recycled. Or using clean energy sources in an environmentally conscious community may increase cost but improve the company's image, reputation, and eventually profitability. Such a problem would require a modeling approach that considers the long-term policy decisions of the company rather than one which would be concerned with individual items or batches during production (Lin et al. 1998). It would look at the manufacturing plant globally as a system to understand its structure and how the structure affects the output. It requires establishing causal relationships between relevant factors. Discrete event simulation involves constructing detailed description of system behavior that at times may not be compatible with a system wide or global point of view of the system.

We propose using system dynamics methodology for modeling and analysis of sustainable manufacturing. System dynamics models systems by determining the relationship between factors. The underlying premise is that the structure of a system gives rise to its behavior. This method involves two major stages in analysis. The first is for the model to be developed from building blocks relating to the cause and effect of the behavior of factors in the system. Secondly, developing a quantitative model and representing it in terms of flow rates, levels and delays. The various factors are interconnected and it is very difficult to study either of these factors in isolation and hope to understand the whole system. This is because no part can be changed without triggering changes over the whole. System dynamics operates by providing for information feedback from output which will accrue as a result of taking certain decisions. We need to discern the effect of adopting given policies on issues such as energy consumption, water usage, material selection, process technology, etc. on the manufacturing plant, environment, and community. We identify four separate domains for analysis, i.e., manufacturing, environmental, financial and social domains. Using these four domains, we propose a framework that can be used for building system dynamics models for sustainable manufacturing. The framework would attempt to ease the inherent difficulties associated with constructing system dynamics models, for example, use of different modeling methods by different researchers, lack of consistent terminology, unavailability of data, abstraction level, art of modeling, etc. Every model has essentially to be developed from scratch and of little value after the intended purpose. Therefore, researchers and analysts are unable to benefit from the work of others through collaborating, sharing, and reusing models and components. Our research is hence focused on development of a framework that will eventually make it possible to build composable sustainable manufacturing model components from different research teams. With this framework it would become easier to construct system dynamics models tailored to specific problems in different industries and geographies with model components acting as the building blocks.

2. LITERATURE REVIEW

The need for development and application of sustainable manufacturing technologies became apparent after the publication of "The Limits to Growth" (Meadows et al. 1972). This publication reports that the global ecological constraints related to resource use and emissions might have adverse effect on development in the twenty first century. A model called World3 was developed using system dynamics to examine five factors of global concern – population growth, industrial manufacturing, agricultural production, non-renewable resources, and environmental pollution. These factors are interconnected in some way, and interact and influence each other. World3 used 12 different scenarios to show how the above factors interact with a variety of the earth's limits and showed that if humanity continues with "business as usual" the limits will force an end to physical growth sometime during the twenty-first century. After more than 30 years a newer version of the model called World3-03 was developed and included additional scenarios. This model is explained in "Limits to Growth – The 30 Year Update" (Meadows et al. 2004).

The model shows that collapse of the natural system and hence of production and the population will be the inevitable result. However, it also shows that if humanity adopts technology that uses renewable resources, controls population growth, and reduces pollution, collapse would be avoided and the resulting world would sustain high living standards and human welfare.

System dynamics is suited for modeling sustainable manufacturing but there has been a limited application of system dynamics for modeling sustainable manufacturing. A few efforts have addressed it as part of modeling sustainable development. Wolstenhome (1983) was perhaps among the first researchers to apply system dynamics to study development and its impact on natural resources, though it was not identified as sustainable development at the time. He used system dynamics to generically model a 5-year development plan of a developing country. The model included natural resources, land, population, food, money, and industrial capacity. The model was used to underline the possibility that development can lead to rapid depletion of natural resources and that the programs tend to err in this direction. Bockermann et al. (2005) compared results of a system dynamics model with an econometric model for sustainability in parts of Europe. The two models were used to test sustainability strategies for their environmental, social, and economic impact. The authors conclude that the results of the two models converged even with the large difference in modeling approaches and scope. The results indicated that a skillful combination of economic, environmental, social, and labor policies is needed to reach a sustainable state.

A few efforts have focused on a specific industry and its impact on the environment. Rehan et al. (2005) report a system dynamics model that can be used to explore policy options for greening the concrete industry in Canada. It combines technical, economic, and market considerations for evaluating policy options. Similarly, Anand et al. (2006) utilize system dynamics modeling to evaluate policies for reducing the CO_2 emissions from the cement industry as a whole in India over a period of 20 years. The authors identified a set of integrated initiatives for reduction of emissions including population stabilization, change in cement composition, increased use of renewable energy, and an energy efficient process with thermal energy recovery from waste heat.

The papers discussed above collectively include factors from three major domains when exploring the impact of manufacturing on the environment. The three domains in addition to manufacturing itself are environmental domain, financial or economic domain, and social domain.

An effort was made to identify previous work related to development of a system dynamics framework for sustainable manufacturing. The intent of such a framework would be to facilitate the development of system dynamics models for exploring sustainable manufacturing. Oyarbide et al. (2003) developed a generic manufacturing simulation tool for simple scenarios based on system dynamics. The tool focuses on modeling manufacturing systems to identify the range of suitable design options that can then be fine-tuned using discrete event simulation. The tool did not take any factors outside of manufacturing into account but it did demonstrate a need to simplify the process of developing system dynamics models of manufacturing. Kantardgi (2003) developed system dynamics models of interactions between industry and environment. He developed a basic model structure incorporating the financial part of a production enterprise and its impact on the environment. The basic model is adapted to two specific scenarios for identifying the impact on environment over time. Tesfamariam and Lindberg (2005) developed a generic systems dynamics model for manufacturing and demonstrated its use with a case study. The model, however, is focused on manufacturing and does not include aspects affecting the environment. Seidel et al. (2008) utilized the systems thinking approach to identify factors that may influence small and medium enterprises (SMEs) to embrace sustainable manufacturing practices. They developed causal loop diagrams for the influence of owner, market and legislative practices on moving towards sustainable practices. They plan to continue the effort towards development of a framework for successful implementation of environmental practices in SMEs.

Kalninsh and Ozolinsh (2006) had a very similar motivation to ours, improving collaboration, sharing and reuse of systems dynamics models through a well defined vocabulary and structured data. They proposed an integrated framework for modeling using system dynamics. The framework is based on use of meta models described using the standards Meta Object Facility (MOF) and is intended for use in modeling social, economic, or business systems. Their proposed approach would facilitate structured input and output of system dynamics model data and secondly, allow the sharing and reuse of data sets that drive model behavior or used to calibrate the model. Our proposed framework in this paper is specific to sustainable manufacturing and may be implemented using a meta modeling approach such as suggested by these researchers.

The literature review indicated that the application of system dynamics to sustainable manufacturing is scattered and shows a lack of a framework as a basis for modeling. It was also noticed that the efforts in modeling manufacturing or production systems used different terminology to refer to the same concepts. For example, Rehan et al. (2005) include “clinker consumption” as a variable in their model while Anand et al. (2006) include “clinker production” as a variable in their model and both appear to referring to the same concept. Similarly, Kantardgi (2003) includes “environmental taxes” and “investments to cleaning technology” in his model, while Seidel et al. (2008) appear to consolidate the two into the variable “financial cost of sustainability” in their model. Such variations in terminology and model construction may hamper the reusability and sharing of models, something that is needed to allow researchers to work closely together to address the complex challenge of sustainable manufacturing.

3. PROPOSED FRAMEWORK

The proposed framework is designed to cater to a flexible scope for a wide number of possible situations and different modeling objectives. The framework should be applicable to modeling sustainable manufacturing from a global level to community level. The proposed scheme is intended to be applicable to these widely varying levels of detail. The resulting models may be used for a range of decisions related to sustainable manufacturing including, for example:

- Comparative analysis of sustainability policies in considered domains
- Evaluation of composition of manufacturing industry within a geographical area
- Identification of strategic manufacturing industries
- Analysis of environmental impact of new manufacturing industry on a geographical area
- Evaluation of policy incentives to attract desired manufacturing industry to a state or community

The proposed framework is described in the following sub-sections.

3.1. High level representation

The four domains relevant to manufacturing sustainability analysis are manufacturing, environmental, financial, and the social domain. Each one of these domains influences the other as represented in Figure 1. For example, the ultimate goal of any manufacturing firm is to make money so as to remain financially viable. Finances are required to fund manufacturing activities such as purchasing equipment and raw materials, pay taxes, and pay workers. Finances would also be required to pay any fines if manufacturing activities do not adhere to environmental requirements. The manufacturer as a financial entity earns revenue from the sale of products in the financial domain. Manufacturing affects the social domain via the manufacturer’s role as a social entity in providing employment for the manufacturing workforce and contributing to the development of community amenities. The social domain provides the market for the products and services. The associated financial transactions are modeled in the financial domain, as is the role of shareholders and the general financial wealth and standard of living that could be a determinant of the success of the manufacturing venture as a financial entity.

On the other hand, the social domain provides labor and expertise for manufacturers as social entities. It also provides the supporting infrastructure and social laws and regulations necessary for maintaining quality of life. Environmentally-conscious manufacturers would be beneficiaries of goodwill and good reputation the society and can contribute to its overall success. The social and the environmental domains interact through the influence of available water, air, and other resources necessary for human life and wellbeing. Lastly, manufacturing domain influences the environmental domain through byproducts, wastes, and toxic or green house gases released by manufacturers as environmental entities. Manufacturing also often uses natural resources as raw materials and energy sources, some of which deplete non-renewable natural resources. All these affect the natural environment. However, in some cases byproducts of manufacturing can be beneficial to the natural environment. The natural environment is a major factor in determining the location of a manufacturing plant and to provide space for landfill.

There are no direct flows between the domains as may be clear by the above discussion. The domains have been organized such that each can be modeled fairly independently with some of the information from other domains provided as variables. The relevant aspects of the manufacturers are represented in the other domains. Manufacturers are represented as corresponding environmental entities in the environmental domain, as corresponding social entities in social domain and as corresponding financial entities in the financial domain. Later discussion of factors within each domain further explains the organization. A stock and flow model of the manufacturing domain has been provided for illustration in the following sub-section. The intent is to develop such models for all the domains once the important factors and taxonomy for all of them has been finalized.

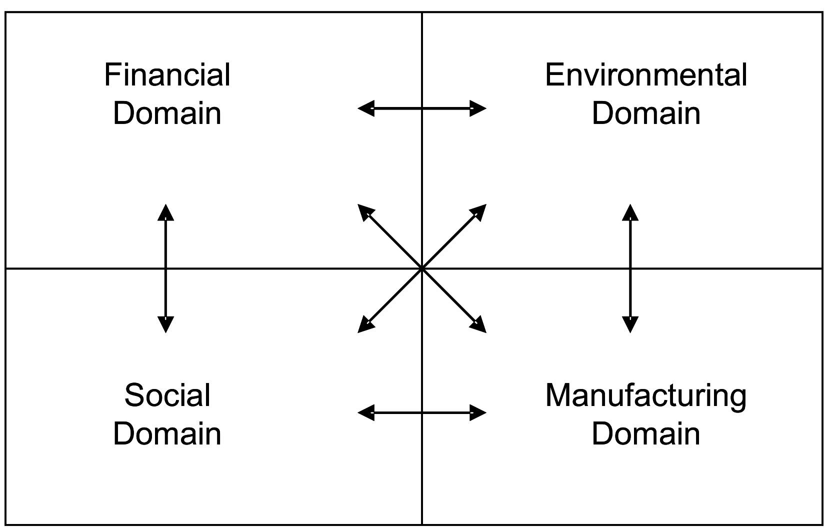

Figure 1. High level representation of the system dynamics modeling framework for sustainable manufacturing.

The following discussion of each of the four domains is presented to support the development of corresponding stocks and flow diagrams. The discussions of the key elements in each sector identifies the associated stocks and flows. In system dynamics modeling "stocks" refers to accumulations that characterize the state of the system behavior and contribute to the information used for decision making (Sterman 2000). Stocks change over time based on the difference of inflows and outflows. Examples of stocks include acres of contaminated land, number of people working in a business and of course, the obvious one, inventories along the manufacturing supply chain.

3.2. Manufacturing domain

The manufacturing system produces final products which get stored as serviceable inventory and includes all elements necessary for manufacturing to take place. There are a number of factors that determine the level of production, for example the installed machine capacity, the number and productivity of workers, and the manufacturing technology. To make these products manufacturing entities rely on availability of energy, water, materials, and other supplies. Other valuable manufacturing inputs include labor and intellectual property. Manufacturing laws and regulations, at the local, state, and federal level determine the guidelines under which industries are run. Manufacturing, like any business, depends on consumers who create the market for the products.

The key elements within manufacturing are categorized as:

- 3.2.1. Inventories
- 3.2.2. Energy
- 3.2.3. Labor
- 3.2.4. Suppliers
- 3.2.5. Manufacturers
- 3.2.6. Retailers
- 3.2.7. Consumers
- 3.2.8. Markets
- 3.2.9. Product variety
- 3.2.10. Waste
- 3.2.11. Transportation capacity
- 3.2.12. Manufacturing regulations
- 3.2.13. Intellectual property
- 3.2.14. Legislative violations

Inventories. The flow of inventory along the supply chain to the end consumer represents the manufacturing activity. The parts of the supply chain that are within the geographical area in the scope of the model should be included. The inventories are modeled as multiple stocks based on location along the supply chain including raw materials, suppliers' inventories, manufacturers' inventories, retailer inventories, products in use, and recycled material inventories. The products-in-use stock may be further divided into those in use with individual consumers and those in use with industrial consumers. The flow rates through successive supply chain stages will be driven by consumer demand that in turn will be influenced by the individual wealth. The input flow for raw materials inventory stock would depend on the availability of recycled materials and those provided from natural resources. Availability of materials could be a major factor in determining the location of the supplier and manufacturing facilities.

Energy. This category includes the power generation capacity as a stock and inventories of fossil-fuels such as oil and natural gas for manufacturing. Energy in the form of electric power is required to run machines and equipment and provide lighting and heating. The flow into and out of this stock depends on installation of additional generators or retirement of equipment. Energy in the form of fossil-fuels may be used for some manufacturing processes such as large furnaces. The flow into this stock will be through inventories provided by energy producers while the flow out will depend on the level of production activities at suppliers and manufacturers and logistics activities for moving the material along the supply chains.

Labor. This category refers to the stock of workforce available for manufacturing. The higher the stock of trained labor in the particular trade of manufacturing the better it should perform. The workforce increase by recruiting and decrease by attrition or dismissal will be modeled in the social domain.

Suppliers. Many plants cannot make all the components that they need to assemble into the final product and they need a stock of suppliers. This category also includes suppliers of equipment that do not form part of the final product such as machines and equipment, and suppliers of consumables such as plant supplies, and office requirements. Suppliers are a stock and can be grouped into suppliers of what goes directly into the product and those of support materials and services for a more detailed treatment.

Manufacturers. The manufacturers are the primary group modeled as a stock in the manufacturing domain. The stock will increase with the availability of right circumstances for manufacturing including a large consumer population, a thriving economy, and availability of sources of energy, labor, and materials. The stock may decrease with absence of the favorable circumstances.

Retailers. This category represents the stock of organizations and people involved in ensuring that the products reach the final consumer. Similar to manufacturers, a large consumer population in a good economy will support increase in this stock.

Consumers. This category is determined by the population in and the individual wealth levels in the geographic area modeled. Consumers create the market within the modeled geography for the manufactured products. The increase and decrease of population will be modeled in the social domain while the individual wealth levels are modeled in the financial domain.

Markets. This category represents the markets for the manufacturers outside the geographic area being modeled. If a nation’s manufacturing industry was being modeled, markets will represent all the export markets for the products manufactured. The existence of external markets will depend on the uniqueness of the products, influenced by intellectual property.

Product variety. A larger product variety may lead to a larger number of consumers and a larger number of manufacturers may be required to service them. A large product variety with a small number of manufacturers may suggest lower efficiencies of production and consequently higher use of resources for the same production volumes. New innovations, represented by intellectual property, would influence the increase in product variety. Product variety may be modeled as a singular stock, but may be grouped into consumer product variety and industrial product variety.

Waste. This category includes the wastes generated from manufacturing activity that are non-polluting and may be sorted into material that can be recycled and the material that has to be sent to land fill. The wastes include edges of cuttings and certain byproducts of manufacturing. Wastes that contain pollutants are modeled in the environmental domain.

Transportation fleets. This stock represents the transportation fleets required to support the manufacturing activity. It includes the fleets required for transportation of raw materials, components, finished products, waste, and recycled materials. The capacity of these fleets could increase or decrease affecting the manufacturing function. The fleets can be modeled as a singular stock or can be sub-grouped by the stage of supply chain they service.

Manufacturing regulations. Manufacturing laws and regulations, at the local, state and federal levels determine the guidelines under which industries are run. Laws are enforced by local agencies. An example of regulations in this category is of intellectual property. A manufacturer with larger number of patents may be able to run a more profitable operation than others.

Intellectual property. This is an asset that manufacturing may possess, which may give it an advantage over competitors. This stock could increase or decrease depending on the firm's innovativeness or laws and regulations.

Violations. This stock models the number of violations of manufacturing regulations by manufacturers. The violations may influence the levels of manufacturers and suppliers. A large number of manufacturing regulations and associated violations may discourage manufacturing investment in the area. However, if the pursued violations are primarily related to intellectual property, it may reflect respect for intellectual rights and may attract innovative manufacturers.

A stock and flow diagram for the manufacturing domain is provided in Figure 2 to illustrate the translation of the above discussions. In the figure, the stocks are represented using rectangular boxes, pipes with arrows pointing in and out as inflows and outflows respectively and rate of the flows as valves on the pipes. Clouds are used to represent sources and sinks that are stocks outside of the boundary of the model. The arrows marked with a positive sign indicate a direct relationship between the factors, that is, an increase in a factor at the tail of the arrow will cause an increase in the factor at the head of the arrow. The arrows marked with a negative sign indicate an inverse relationship between the factors. Similar diagrams will be developed in future for the other three domains.

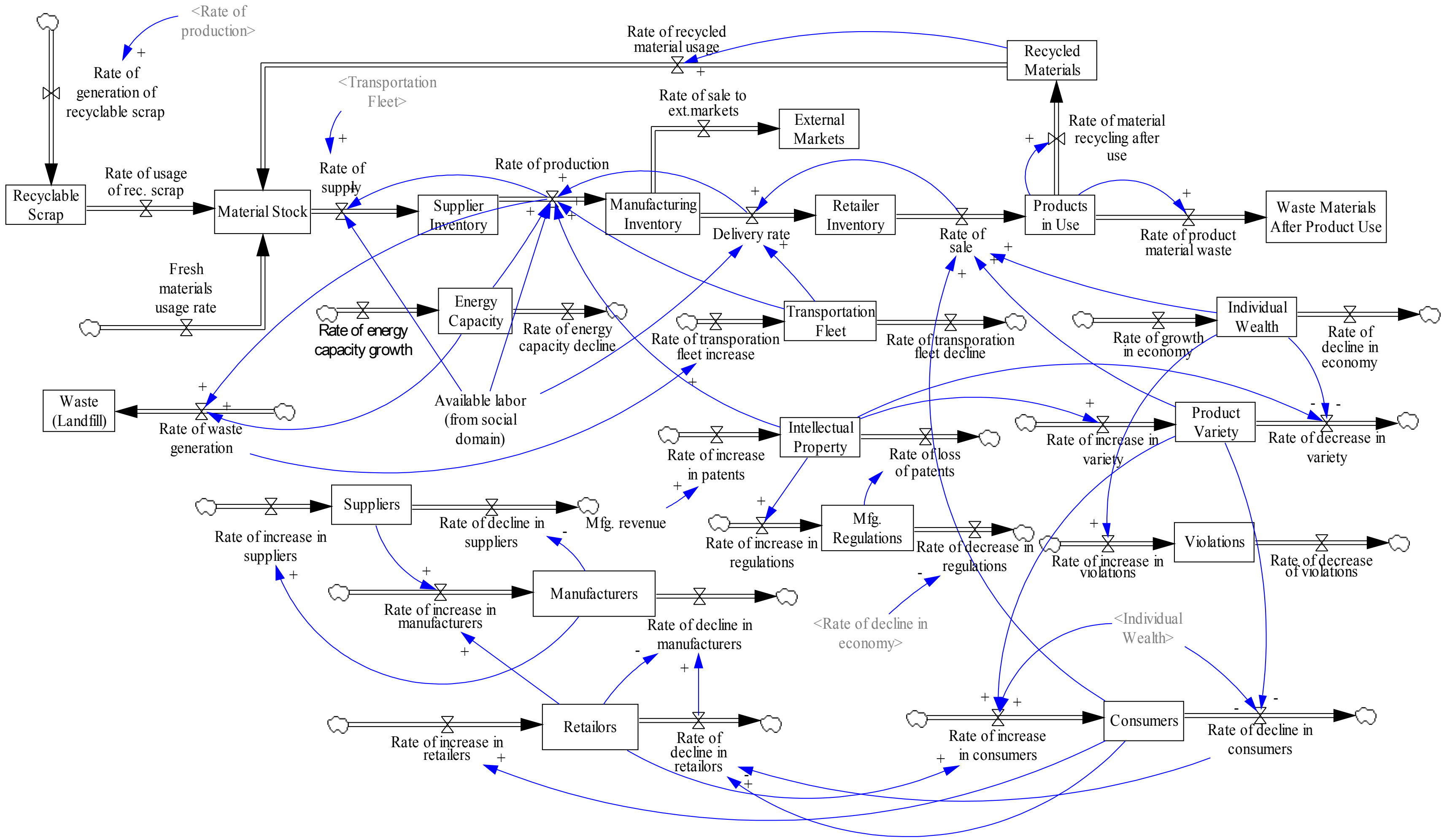

Figure 2. Manufacturing domain model

3.3. Environmental domain

The primary objective for sustainability in the environmental domain is to reduce the pollution and the pace of consumption of natural resources. In "*Limits to growth*" (2004) it is argued that we should limit pollution to a level where the existing systems can clean up the effluent or waste, and reduce consumption of natural resources such as energy and materials, using efficient processing technology, to a level where there is enough time to develop and substitute with renewable ones.

The environmental domain includes all the elements that may be affected by activities in the manufacturing domain. The flows within the sub-model corresponding to this domain will primarily consist of pollutants and other by-products from manufacturing and other sources that are released into the environment. The pollutant flow will include those generated by manufacturing and support activities and those removed by clean up activities. They may also include pollutants generated by other sources such as plant life and animal life if relevant to the geographical area being considered corresponding to the manufacturing domain. The other by-products may include clean water and non-polluting gases released to nature as outputs from manufacturing processes and from pollution control devices such as scrubbers and cleaning devices. The modeled flows in this domain may also include outflows of natural resources from associated stocks to model their use by manufacturers and energy producers.

The key elements that may be modeled in this domain can be classified in the following categories.

3.3.1.Water
3.3.2.Atmosphere
3.3.3.Land mass
3.3.4.Plant life
3.3.5.Animal life
3.3.6.Non-renewable resources
3.3.7.Environmental regulations
3.3.8.Manufacturers as environmental entities
3.3.9.Transportation fleets as environmental entities
3.3.10.Energy producers as environmental entities
3.3.11.Clean-up companies

Water. This category may include stocks such as clean water, polluted water, and drinkable water within the geographic area being modeled. A rate of release of pollutants may influence the flow from clean water stock to polluted water stock. For models with a narrower scope of modeling a single manufacturing entity or a few of them, the polluted water release over the simulation horizon may be tracked as a stock.

Atmosphere. This category may include stocks such as green house gases, particulate matter in air, and volatile organic compounds. Both primary and secondary pollutants should be defined as stocks. The flow of pollutants from manufacturing and other sources into atmosphere would change the level of such stocks.

Land mass. The stocks in this category may include preserved land, contaminated land, and swamps. Similar to earlier categories, dumping of pollutants from manufacturing installations in land fills or on to land would change the level of such stocks.

Plant life. The stocks in plant life would vary based on the characteristics of the area in the scope of the model and may include agricultural crops, woody perennials, and forest cover. The plant life stocks will define the rate of pollutant release from them, such as the release of carbon monoxide from decay of chlorophyll in plants. The increase in pollutants in the area, with contribution from manufacturing, may lead to reduction in plant life stocks.

Animal life. Again the stocks would vary based on the animal life in the area being modeled and may include insects, birds, domesticated animals, and wild animals. The animal life stocks will determine the rate of pollutant release from them, such as release of methane from cattle.
Similar to plant life, the animal life stocks may be affected by increase in pollutants in the area including contribution from manufacturing.

Non-renewable resources. The stocks in the non-renewable resources category may include those that are used for supporting manufacturing or energy productions such as metals and coal. The stocks may be depleted if they are used by manufacturers or energy producers in the geographical area modeled. They may also contribute to release of pollutants to environment through by-products from processes used for their extraction.

Environmental regulations. At a coarse level, the environmental regulations may be modeled as stocks and grouped by applicability such as regulations for manufacturing, for plant life, and for animal life. The higher the number of such regulations, the less the flow of pollutants from corresponding entities. Alternatively they can be divided by type such as regulations for plant life, for animal life, for non-renewable resources, and for manufacturing. Regulations for manufacturing may encourage use of pollution control devices and impact the rates of release of pollutants and by-products.

Manufacturers as environmental entities. The manufacturers may be grouped into various stocks based on the type of pollutants and by-products generated such as, chemical manufacturers, automobile manufacturers, and food manufacturers. The open market forces would determine the increase or decrease in the number and size of such manufacturers over time. It should be noted that for the purpose of this domain, manufacturer entities include both suppliers and manufacturers defined in the manufacturing domain.

Transportation fleets as environmental entities. The transportation fleets that serve manufacturing contribute to the pollution attributable to the manufacturing industry. They can be modeled as a singular stock or can be sub grouped by the type of transportation such as trucks, rail cars, ships, and cargo airplanes for more detailed treatment of the different levels of pollutants generated by these different fleets.

Energy producers as environmental entities. The energy producers may be grouped by energy source. At a coarse level, they may be grouped by renewable energy source and non-renewable energy sources. At a more detailed level, they may be grouped by source type used such as producers of coal energy, nuclear energy, hydroelectric energy, and solar energy.

Clean-up companies. The clean-up companies may be modeled as a singular stock. A large number of clean-up companies will provide quick response to clean-up needs at competitive costs. Alternatively, they can be grouped by expertise such as soil remediation and water body remediation.

3.4 Financial domain

The financial domain includes all functions that relate to the income and expenditure of the firm. Hence, the dynamics of the financial subsystem is centered at operating capital for the business because of its level of importance. Finances are required to pay for materials, wages, taxes, and fines. The funds available for running an organization for both day-to-day and long term investments are represented as a stock. Operating capital is increased by revenue from sales and investment income. The amount of this capital required to run the business could be a determining factor in giving out dividends at the end of a period or not. If the net profits after paying income taxes are below a given level or there has been a loss during the period no dividends are given. Operating capital can also be boosted by borrowing from financial institutions or selling stock.

The categories involved for sustainable manufacturing are:

3.4.1.Financial markets
3.4.2.Financial regulations
3.4.3.Financial institutions
3.4.4.Shareholders
3.4.5.Individual wealth in the community
3.4.6.Manufacturers as financial entities
3.4.7.Manufacturing profits
3.4.8.Manufacturing investments
3.4.9.Fines
3.4.10.Taxes
3.4.11.Unemployment benefits
3.4.12.Clean up funding

Financial markets. This category includes institutions that enable the firm to raise operating capital and/or market products. This is modeled as a stock and can be raised by the vibrancy and development of these markets. They are reduced by economic downturn.

Financial regulations. This is a stock of requirements and guidelines that are subjected to financial institutions to ensure they operate openly and frankly. The more stringent they are the higher the stock and would determine the success of the firm's investments.

Financial institutions. These institutions include banks, insurance companies, and investment funds. The stock of these institutions increases the chances of raising operating capital through borrowing and returns from investment in them.

Shareholders. This category includes those that legally own some share of stock in a joint stock company. They can determine the direction manufacturing can take and increase their ownership by purchasing new shares issued by the company. The stock of shareholders can decide or determine on their share of the companies net income.

Individual wealth in the community. This refers to the standard of living which would determine the ability of people in a community to pay for the firm's products. We can also refer to this as the purchasing power. This is a stock with effect on financial health of the firm and can increase or decrease depending on state of the local economy to which the firm contributes. A reduction in individual wealth will influence the housing occupancy modeled in the social domain.

Manufacturers as financial entities. This stock will be used to represent the manufacturers in the financial domain. An increasing number of financially successful manufacturers will help improve the general economy. On the other hand, a worsening economy may reduce the number of manufacturers due to lack of investments and credit lines.

Manufacturing profits. The ability of manufacturing sector to generate profits will influence many aspects including continuity as an enterprise, hiring levels, contributions to society and funding for research and development that may lead to increase in intellectual property. At a coarse level, the profits may be modeled as a singular stock, while they may be split by profits of component industries such as chemical, automobile, and industrial products.

Manufacturing investments. The channeling of investments in manufacturing will help increase the number of manufacturers and/or help increase production rates for existing manufacturers. The investments may also play a similar role as the manufacturing profits but would generally be used for longer term goals. Again, the manufacturing investments may be modeled as a singular stock or split by component industries for a more detailed treatment.

Fines. Fines are imposed by regulatory authorities for non compliance. In case of environmental regulations this refers to the limits of pollution and emissions. It could also include the minimum percentage of the final product that must be made of recyclable materials and collection percentage of discarded products. The stock of types of fines could increase level of compliance with environmental requirements but in some cases restrict the firms profitable operations.

Taxes. This is the category that includes all local, state, and federal levy on products sold or consumed. In some cases, environmental taxes are imposed in response to effluents discharged. The higher level of stock of taxes could affect manufacturing operations.

Unemployment benefits. This is a stock that increases over time due to payments by manufacturing and government funding and decreases through payments to individual who are unemployed. The better the state of the economy the fewer are the people receiving unemployment benefits and the lower the outflow from this stock.

Clean-up funding. The clean-up funding may be modeled as a singular stock for funding earmarked for environmental clean-up efforts. For a more detailed treatment the funding sources may be grouped by the focus of funding such as for site cleanup and for incentives for installation of pollution control devices.

3.5. Social domain

The primary objective in the social domain is to maintain a high quality of life. A person enjoying good quality life should among other things, earn enough to satisfy personal needs, live in a community with good social amenities, and live in an environment free of pollution. And manufacturing entities in the community are a major player in all the above. The social domain has a direct influence on the manufacturing domain through the availability of the manufacturing workforce. The social domain also influences the manufacturing domain indirectly through financial and environmental domains. The relevant elements of the social domain are those that have an influence on the other three domains, are influenced by them, and/or are major actors in this domain. The flows in the social domain include people and entities that comprise the social system such as institutions and amenities.

The key elements to be modeled in the social domain can be grouped as below.

3.5.1.General population
3.5.2.Manufacturing workforce
3.5.3.Housing
3.5.4.Community amenities
3.5.5.Manufacturers as social institutions
3.5.6.Supporting infrastructure and institutions
3.5.7.Social laws and regulations

General population. The general population stocks may be grouped in several different ways. The stocks may include:

- Total population with increase through immigration and births and decrease through emigration and deaths
- Employed and unemployed, connected with flows influenced by the economy
- Healthy and sick population, connected with flows influenced by environmental pollution
- Law abiding citizens and criminals, connected with flows affected by unemployment levels and stocks of supporting infrastructure and institutions
- Happy and unhappy people, connected with flows affected by a number of factors including unemployment levels, ratio of healthy and sick, ratio of criminals and law abiding, and average commute time.
- Environmentally conscious and environmentally apathetic. The environmentally conscious would consider manufacturers' environmental reputation and goodwill in making purchasing decisions. The flows among the conscious and the apathetic people may be influenced by pollution levels modeled in environmental domain.

- Upper, middle, and lower income groups, connected with flows affected by levels of employment. These stocks will affect consumption of consumer products.

Manufacturing workforce. The manufacturing workforce stocks may be grouped into white collar, skilled labor, and unskilled labor. The flows among these stocks will be affected by availability of education and job training benefits provided by a socially conscious manufacturer and availability of such programs to the general population that may be afforded by a growing economy. The stocks may also include healthy and sick workers affected by worker safety programs, health and recreational benefits provided by a socially conscious manufacturer. Finally, the stocks may also be grouped into employed and unemployed with the flows affected by the financial status of the manufacturers.

Housing. The stocks in this category may be grouped as single family, multi-family, and public housing units. They may also be grouped as vacant and occupied to indicate the impact of economic slowdown.

Community amenities. The stocks in this category may be treated as a singular stock or split into parks, recreational facilities, etc. They may also be grouped into well maintained or run-down with the flow among them affected by availability of funding provided by communities and socially conscious manufacturers.

Manufacturers as social institutions. The manufacturer stocks may be grouped into successful and struggling ones with impact on other stocks such as employed and unemployed manufacturing workforce. The stocks may also be grouped into socially conscious and socially apathetic with impact on community amenities and manufacturing workforce stocks. It is assumed that socially conscious manufacturers maintain good reputation and goodwill among the community and that would have an impact on the purchase decisions of the population.

Supporting infrastructure and institutions. These stocks may be grouped into socially important entities such as public transportation, hospitals, daycare, and school systems. They may also be grouped into operating well and struggling institutions with the connecting flows affected by state of the local economy and availability of any external funding.

Social laws and regulations. The social laws and regulations may be grouped into a singular stock for a high level model with the assumption that too few or too many regulations will negatively affect the social environment as reflected by flows from happy to unhappy population stocks. For a detailed treatment they may be split into regulations affecting stocks listed above including population, workforce, housing, amenities, and supporting infrastructure and institutions.

4. FURTHER DEVELOPMENT OF THE FRAMEWORK

The framework concept described in the preceding sections is a first step in a process towards development and acceptance of a standard system dynamics modeling framework for sustainable manufacturing. In addition to the framework, a number of associated artifacts will need to be developed to achieve the goal of multiple teams collaborating across the globe, sharing and reusing models, and data sets to address the important issue of sustainable manufacturing. The process anticipated for this development is briefly outlined below.

- *Framework concept development.* The concept described above will be updated based on feedback from the system dynamics community and sustainable manufacturing researchers through presentations at related conferences and workshops. The taxonomy will be improved to reflect an accepted set by researchers in social, economic, environmental, and manufacturing domains. An attempt was made to identify relevant taxonomy standards but none were located that were publicly available or approved by standards organizations.

- *Standard reference models.* A set of reference models will be developed based on the framework. The development of the models will allow opportunities of collaboration among researchers. The resultant models will provide guidance to other researchers for building and applying system dynamics models for sustainable manufacturing in specific geographic areas. The reference models will address multiple scopes ranging from global to a community level. The development of these reference models will also serve to verify the framework. The framework may be updated to include additional factors based on any missing issues identified during the development of the standard reference models.

- *Composable models*. The framework will support development of composable models. Separate teams of researchers can focus on developing complementary parts of the model and bring them together. For example, models for the four identified domains can be developed separately and integrated. With a clearly defined framework it is also possible to build shareable reusable model components within each of the four domains. A set of model components should be built for an identified scope and integrated to test the concept. Over time, researchers may develop and provide model components in on-line libraries.

- *Neutral interfaces.* Defined neutral interfaces for instantiating the models with data will allow rapid development and use. The neutral interfaces may be defined using an information modeling language such as an XML schema for the identified scope of sustainable manufacturing data. The development of neutral interfaces will require involvement of current vendors of system dynamics modeling software. Their support will also be required for providing capabilities for reading files based on XML neutral interfaces.

- *Test data sets*. The definition of neutral interfaces will enable development of test data sets based on well documented cases. The test data sets can be used by researchers to evaluate new models. The capability of new models to generate results that closely match those defined in the test data sets will improve confidence in the new model. In turn, when the new models are applied to real life situations, the recipients of the results will have a higher comfort level.

- *Verification and validation guide*. The availability of the framework and other artifacts will support development of a well-defined verification and validation guide for system dynamics models for sustainable manufacturing. The guide can outline the steps based on verification of the model against the framework and validation using the test data sets.

- *Visualization*. Definition of neutral interfaces will also enable defining common approaches for visualization of results. Use of common visualization mechanisms will further help collaboration through a rapid common understanding of modeled phenomenon and results.

5. CONCLUSION

The world faces a major challenge due to a deteriorating global environment and the aspirations of the global population for a high quality of life. There is a critical need for ensuring that all future development efforts are sustainable. A major component of development and ensuring high quality of life is provided by the manufacturing sector of the economy. Yet manufacturing consumes natural resources and produces by-products and waste, often detrimental to the environment. The global research community has to come together to develop approaches and policy guidance for sustainable manufacturing. System dynamics modeling provides an effective technique for application of systems thinking to sustainable manufacturing, understanding the impact of structure of the systems in relevant domains, and evaluation of policies intended to promote sustainable manufacturing practices.

This paper presented a proposal for a system dynamics modeling framework for sustainable manufacturing with the goal of facilitating collaboration among researchers across the globe working on this important topic. The framework organizes the relevant factors in four domains: manufacturing, environmental, financial, and social, and proposes a set of influential factors within each domain identified in an acceptable common taxonomy. These factors are intended to form the basis for developing system dynamics models as researchers explore and determine the structure of relationships among individual factors within and across different domains. A set of associated artifacts are also proposed for achieving the overall goal.

It should be noted that the description of the framework and associated terminology is a proposal, intended to facilitate discussion on this important topic and gather feedback for its improvement. Readers are encouraged to provide feedback to the authors to support further development of the framework.

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