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A FRAMEWORK FOR MULTI-RESOLUTION MODELING OF SUSTAINABLE MANUFACTURING

Sanjay Jain

The George Washington University
2201 G Street NW, Suite 415
Washington, DC 20052, USA

Deogratias Kibira

National Institute of Standards and Technology
100 Bureau Drive, MS826
Gaithersburg, MD 20899, USA

ABSTRACT

This paper proposes a multi-resolution framework for application of system dynamics modeling to sustainable manufacturing. Sustainable manufacturing involves interaction of four complex systems namely manufacturing, environmental, financial, and social domains. The proposed framework integrates model components corresponding to the four major domains. Conceptual models are proposed at two levels of resolution for each of the four domains with models provided in this paper for the manufacturing domain.

1 INTRODUCTION

Modern manufacturing consumes large amounts of resources, generates waste, and pollutes the natural environment. One can ask a question as to whether continued industrial expansion and manufacturing production in the current manner would be sustainable in the long term. 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, and 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 three aspects of people, planet, and profit have to be considered for assessing a company's performance.

1.1 Sustainability Concepts in Models of Manufacturing Systems

Many of the factors involved in sustainable manufacturing interact, influencing, restricting, and depending on each other. That is why we propose using system dynamics methodology for modeling and analysis of sustainable manufacturing. We identify four separate domains for analysis, i.e., manufacturing, environmental, financial, and social domains. We model manufacturing as a separate domain to allow its detailed modeling and to understand impact of manufacturing decisions on the other three 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 problems of lack of consistent terminology, unavailability of data, abstraction level, art of modeling, etc. Majority of models in practice are essentially developed from scratch and are of little value after serving the intended purpose. Therefore, researchers and analysts are unable to benefit from the work of others through collaborating, sharing, and reusing models and components. 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.

1.2 Multi-Resolution Modeling

Multi-resolution modeling refers to the capability of executing the complete model or parts of the model at different levels of resolution corresponding to the question being answered with their use. Low resolution models may be used for answering long term questions while high resolution models may be used for answering near term questions; this can be achieved by changing the resolution of the whole model. If the goal is to understand the impact of detailed level decisions in one part of the model on the other parts, the part of the model that is of interest may be executed at a higher resolution level than others. The resolution of other parts of the model may be reduced by replacing the details with approximate representations. While the concept can be easily described, there are multiple demanding challenges in multi-resolution modeling identified by Tolk (2006).

Incorporating sustainability aspects in manufacturing models will require a large scope since such aspects manifest themselves over a long time and geographies away from the manufacturing system. The long term and geography issues need not be modeled at the same level of detail as some of the manufacturing system aspects. Multi-resolution modeling is thus suitable for studying sustainable manufacturing.

An initial proposal is made in this paper with respect to multi-resolution modeling. Model components at varying level of details are proposed within the same system dynamics simulation software to avoid the issues of time synchronization and interfacing among the components.

2 LITERATURE REVIEW

System dynamics is suited for modeling sustainable manufacturing but literature review on the subject particularly on a modeling framework, is still scanty. A few reported 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. Hjorth et al. (2006) model issues such as human needs, economic capital, population growth, waste generation, and life supporting systems.

Some efforts have focused on modeling operations of specific industry types and their impact on the natural 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. Similarly, Anand et al. (2006) model specific operating policies designed to reduce CO_2 emissions over a period of 20 years in the cement industry. Vlachos et al. (2007) model the complexity associated with collection of used products in reverse supply chains. The papers discussed above collectively include factors from three major domains when exploring the impact of manufacturing on the environment; the environmental domain, financial or economic domain, and social domain.

Regarding a framework: Oyarbide et al. (2003) developed a generic manufacturing simulation tool based on system dynamics for simplified scenarios. The tool focuses on modeling manufacturing systems to identify the range of suitable design options that can 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) constructed 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. 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.

Kalninsh and Ozolinsh (2006) had a very similar motivation to ours, i.e., 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 Meta Object Facility (MOF) standard 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 uses a meta modeling approach 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 affecting emissions in cement manufacturing while Anand et al. (2006) include "clinker production" as a variable affecting emissions 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 that is needed to allow researchers to work closely together to address the complex challenge of sustainable manufacturing.

3 PROPOSED FRAMEWORK

A framework is a classification schema that defines a set of categories into which various concepts or artifacts can be arranged. 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 Conceptual Representation of the Framework

The 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 improve shareholder value 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. 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.

There are no direct flows between the domains since manufacturing is represented as an entity in each of the other domains. 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. Such models have been developed for all the domains but are not being shared due to paper length constraints.

The following discussion of each of the 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).

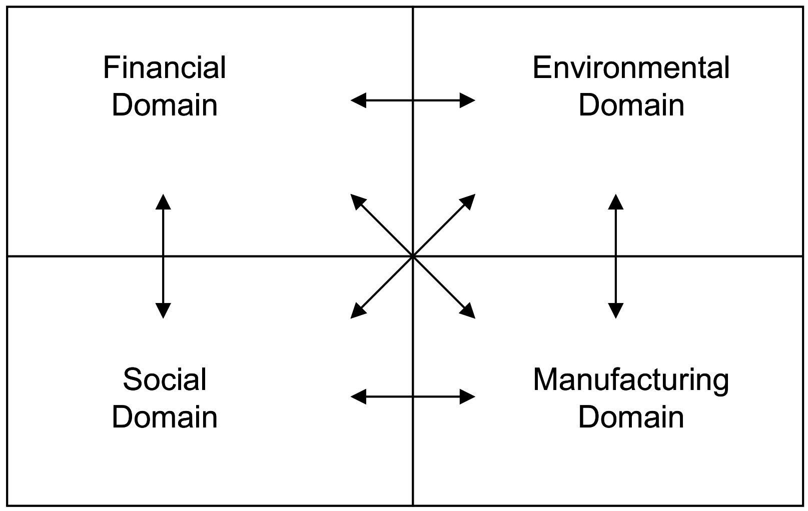

Figure 1: Conceptual representation of the system dynamics modeling framework for sustainable manufacturing.

We first present all elements deemed relevant in the different domains. Models have been developed at two resolution levels for each domain. Due to space restrictions, only the manufacturing domain models are presented at the two levels. Similar models have been developed at the two resolution levels for the other three domains.

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. The key elements within manufacturing are categorized as:

Inventories. The flow of inventory along the supply chain to the end consumer represents the manufacturing activity. The relevant items are those in parts of the supply chain that are within the geographical area in the scope of the model. The inventories are modeled as multiple stocks based on location along the supply chain including fresh raw materials, local suppliers' inventories, manufacturers' inventories, wholesaler and retailer inventories, products in use, and recycled material inventories.

Energy. This category includes the power generation capacity as a stock and inventories of fossil fuels such as oil and natural gas for manufacturing. Electrical energy 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. The energy sources available would be a determining factor for manufacturing investment in a geographical area.

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. 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. Suppliers can also be either locally based or external.

Manufacturers. The manufacturers are the primary group modeled as a stock in the manufacturing domain. The stock will increase with the availability of favorable 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 both inside and outside of the geographic area being modeled. If a nation's manufacturing industry was being modeled, external markets will represent all the export markets for the products manufactured. The existence of external markets will depend on quality and 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. 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.

Local scrap recycling capacity. This represents the local processing capacity of the scrap generated from disposed products after use. It is assumed that the products would be collected. This requires a *local recycling collection capacity*. Some of the scrap is processed external to the local area under consideration.

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. Some of the products are discarded locally, some externally.

Transportation fleet capacity. 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 fleets can be modeled as a singular stock or can be sub-grouped by the stage of supply chain they service.

Number of 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.

Legislative 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.

Investor incentives. This includes the number of favorable and attractive conditions that federal, state, or local administration can put in place to attract investments in manufacturing. These include income tax breaks, reduction of tariffs on imported manufacturing inputs, and favorable depreciation calculation regimes. *Disincentives* are the opposite and are designed to discourage some types of investments in the location.

Economic growth. Overall economic growth in a location would improve employment prospects thereby increasing disposable income to improve the local market. Local economic growth would create this local market and external growth, the external market for the products.

The key elements listed above can be used to model the manufacturing domain using the system dynamics approach. system dynamics models are generally implemented in software using stock and flow diagrams. In such diagrams, 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 polarity assigned to the arrow indicates the direction in which the dependent variable changes in relation with the independent variable an inverse relationship between the factors. The changes themselves are represented using differential equations and are not show in the diagram.

Figure 2 shows the stock and flow diagram for the manufacturing domain at medium resolution level and hence only the major variables from the above list are used. Figure 3 shows the model at high resolution level and incorporates representations of all the variables in the above list. The model resolution is changed from high resolution level to medium resolution level by replacing the detailed representations with approximations that are incorporated in the differential equations for associated changes.

3.3 Environmental Domain

The primary objective for sustainability in the environmental domain is to reduce pollution and the pace of consumption of natural resources. 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 key elements that may be modeled in this domain can be classified in the following categories.

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. In more detailed modeling we can also identify water that is currently within the plant and internally cleaned water that is internally cleaned before reuse.

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. With the atmosphere, our concern is the air quality and how it is affected by current and proposed manufacturing investments.

Land mass. The stocks in this category may include preserved land (pristine landmass), contaminated land, and swamps. Similar to earlier categories, dumping of pollutants from manufacturing installations in landfills 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. With minimal pollution, new plant life can emerge.

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.

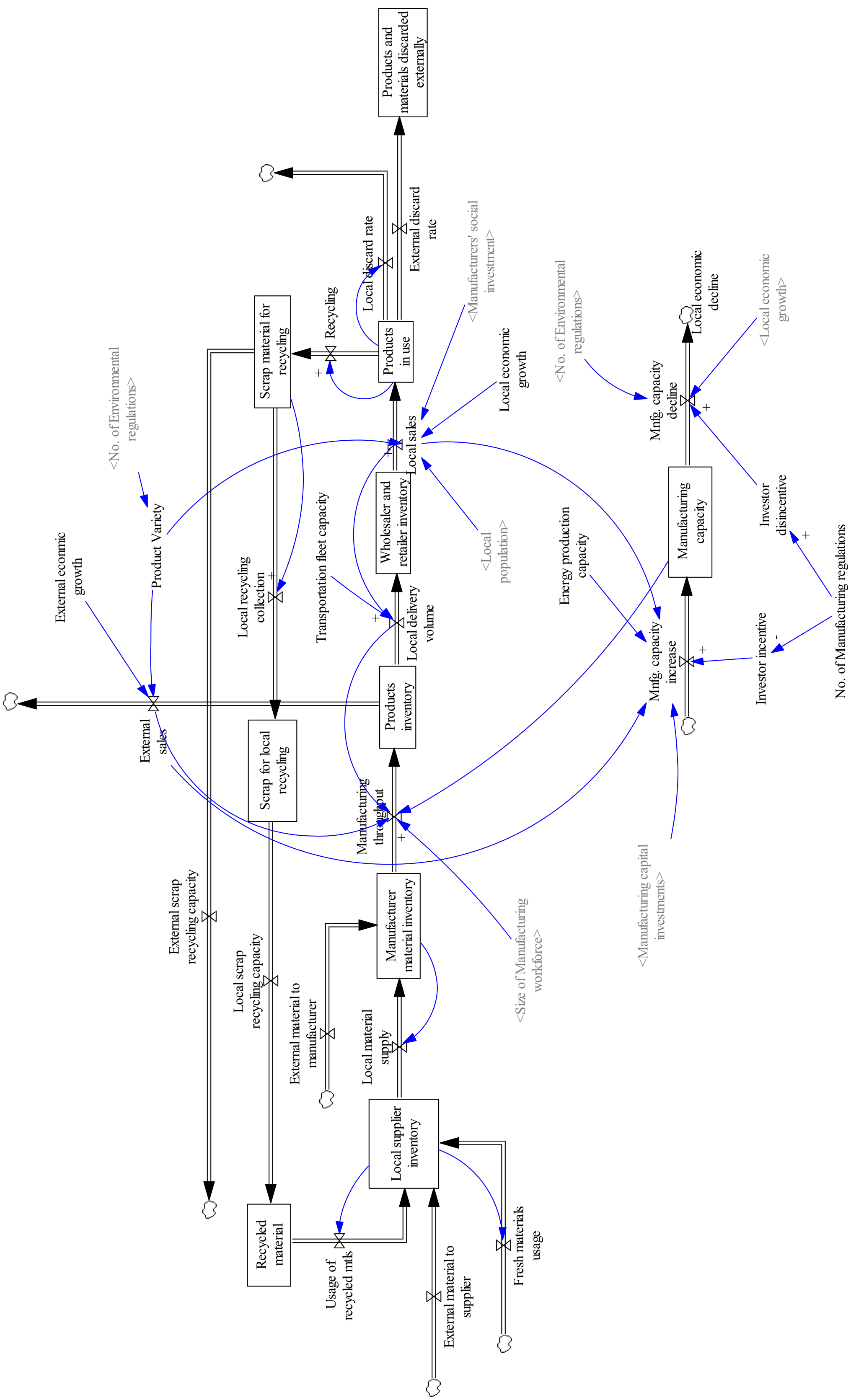

Figure 2: Manufacturing domain model at medium resolution level.

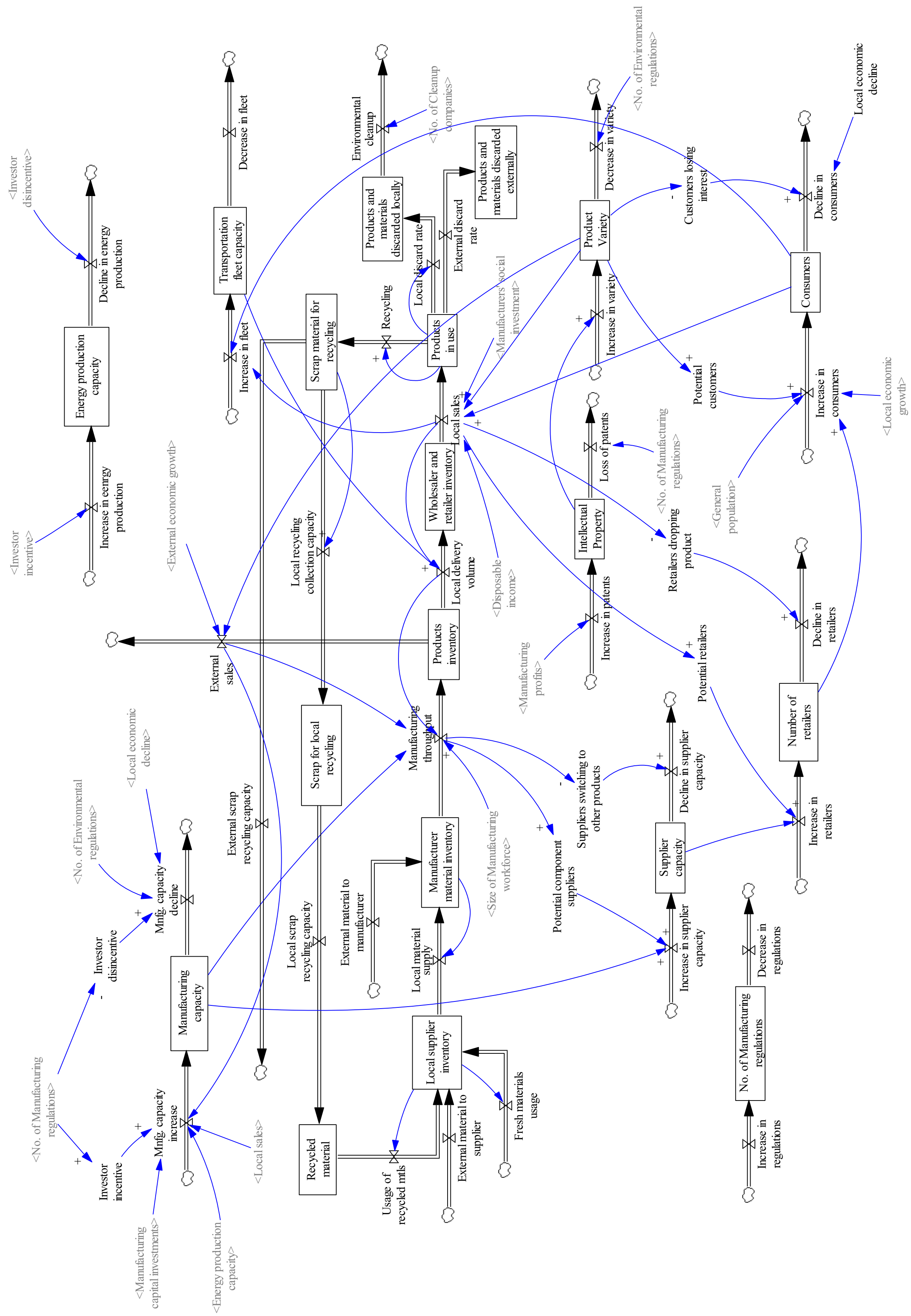

Figure 3: Manufacturing domain model at high resolution level.

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.

Number of 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.

Waste by-products. All manufacturing activities including those of suppliers produce waste by-products, which could be both solid and liquid. These products could have implications on fines and markets for the products. Clean-up companies remove both waste by-products and discarded products from the environment.

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. The categories involved for sustainable manufacturing are:

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 company's net income.

Individual wealth in the community. This refers to the standard of living that would determine the ability of people in a community to pay for the firm's products. We assume that the higher the individual wealth the more the disposable income or 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. The higher the manufacturing throughput the higher the revenue and income from the sale of products will be.

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, or other industrial products.

Manufacturing investments. The channeling of investments in manufacturing will help increase the number of manufacturers and/or raise the production levels for existing firms. Ploughing back profits as investments can help achieve longer-term goals. 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 on pollution and emissions. It could also include the minimum percentage of recyclable materials in the final product 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 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 in an environment free of pollution. And manufacturing entities in the community are a major player in all the above. The key elements in the social domain fall under the following categories:

General population. The general population stocks may be grouped in several different ways. The stocks may include skilled and unskilled persons, employed and unemployed, connected with flows influenced by the economy, and 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. 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 can contribute to amenities as part of their social investment.

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 lower resolution 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 CONCLUSION

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.

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

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AUTHOR BIOGRAPHIES

SANJAY JAIN is an Associate Professor in the Department of Decision Sciences, School of Business at the George Washington University. He is an associate editor of the *International Journal of Simulation and Process Modelling* and a member of the editorial board of the *International Journal of Industrial Engineering*. His research interests are in application of modeling and simulation to complex scenarios including homeland security and supply chains. His web-page address is <http://business.gwu.edu/faculty/sanjay_jain.cfm> and his email address is <jain@gwu.edu>.

DEOGRATIAS KIBIRA is a Senior Lecturer in the Department of Mechanical Engineering at Makerere University in Uganda where he teaches Manufacturing and Quality systems. He has wide research experience in manufacturing simulation and production scheduling. He is currently a Guest Researcher at the National Institute of Standards and Technology where he is part of the research team developing lifecycle information models for sustainable manufacturing. He has a first class honors degree in Mechanical Engineering from Makerere University and Masters and PhD degrees in Manufacturing Engineering from the University of New South Wales, Australia. His e-mail address is <kibira@nist.gov>.