

UNDERSTANDING AND MODELING SUSTAINABILITY ISSUES IN FACILITY LOGISTICS

Brett A. Peters
Texas A&M University

Astrid Garcia Ramos
Universidad Industrial de Santander

Abstract

Environmental issues have been the focus of much discussion and debate. In light of environmental concerns, many companies have focused on creating sustainable products and systems. While there is still much disagreement about what is “sustainable,” there is a lot of on-going activity cover a wide range of areas and topics. However, relatively speaking, there is much less attention and activity within a facility logistics context. In this paper, sustainability issues related to facility logistics are explored. An overview of existing related research across a range of areas is provided. Major issues of concern for facility logistics will be discussed and appropriate decision tradeoffs will be characterized to develop potential research issues related to sustainability with the context of facility logistics and closely related topics.

1 Introduction

Much attention recently has focused on environmental impacts and sustainability issues across a variety of domains. Concerns about global warming and other environmental issues due to emissions from burning carbon-based fuels are driving a search for alternative, green-energy generation technologies. Concerns about water contamination are driving debate about the use of hydraulic fracturing for extracting oil and gas from tight shale formations. Desire to reuse and recycle products and materials has opened up new markets and brought about new regulations, e.g., take-back requirements for certain major product classes in Europe.

Within a facility logistics context, however, sustainability issues have received little attention, although related areas in logistics have seen some growth and activity. Research has focused on reducing emissions and other environmental costs through optimization of transportation and distribution [1]. Closed-loop supply chains, and similar structures, have been investigated to facilitate product recovery and recycling [2]. From a

manufacturing perspective, changes in product design to utilize different raw materials or adjustments to more environmentally friendly manufacturing processes have occurred [3]. While research in these areas is on-going and far from mature, it outpaces what has been seen within facility logistics.

Environmental issues within the facility have been primarily driven by other disciplines. Architects have improved energy efficiency of buildings through a number of techniques and have developed the LEED certification system to evaluate performance. Industrial commissioning studies have focused on reducing energy usage from HVAC and lighting in both industrial and commercial office buildings. Equipment manufacturers have endeavored to lower the energy consumption of their product offerings but only in an independent, stand-alone manner.

This paper explores the sustainability issues related to facility logistics, including the impact of layout design, material handling, and operational planning activities. It highlights existing research related to sustainability within the facility and in related areas. It identifies and discusses major issues of concern from an application perspective and considers appropriate decision tradeoffs required to incorporate sustainability into the analysis. It delineates potential research issues related to sustainability in facility logistics. Preliminary modeling and analysis demonstrates the potential applicability of these research topics.

2 Background and Previous Work

Across all facets of industry, there is an increasing focus on assessing and reducing the environmental impact of operations and on creating sustainable approaches to production and distribution of goods and services. Beginning with product design, companies have looked to reduce the amount of material used or change the type of material to a more environmentally friendly alternative. For example, Apple claims to have reduced the amount of material consumed in its computers by making the systems smaller and lighter. They have also focused on eliminating toxic materials used in the manufacturing of their computer products [4].

Additionally, there has been an emphasis on reducing and transforming the materials used for packaging products for distribution and sales. A common example is the reduced amount of plastic used within disposable water bottles [5]. Dell has an entire program focused on reducing the amount of material required for packaging their products for shipment. They have also begun using bamboo to replace Styrofoam in the packing materials for some laptop computers and other small products. They are even developing mushroom-based cushioning materials for their larger computer systems [6].

Another area of considerable attention is the overall reduction of energy consumption. Recently, companies have attempted to create carbon footprint and emissions “scorecards” to describe the environmental impact of producing products. Companies have developed alternative manufacturing processes to replace those with negative environmental impact or those that have drawn increased public scrutiny, e.g.,

plating processes [7]. Reduction of environmental impact is also exhibited through emissions reduction by cleanup of effluent waste streams [8] or scrubbers on exhaust vents, which have been common on large-scale power plants but are now used across a wide variety of industrial facilities [9].

Energy efficient facilities provide another avenue for companies to promote sustainable practices through reduced energy consumption. Industrial assessment activities, including those sponsored by DoE [10], focus primarily on improved HVAC and lighting performance. Many manufacturing and production facilities also have opportunities to improve energy efficiency through capturing waste heat from industrial processes and using this heat for building HVAC or other useful purposes [11]. Research continues in a wide variety of aspects related to capturing and using waste heat, e.g., as in [12].

Companies have also increased their sustainability efforts by enhancing the efficiency of individual processing equipment through the use of lighter weight materials and reduced energy consumption. These advances have occurred in processing equipment, e.g., CNC machines [13, 14], and as well as in material handling equipment, e.g., advances in electric forklifts [15] and the continued development of alternative power sources, such as fuel cells [16], or the improvements in energy efficiency of conveyor systems [17, 18].

While these efforts are valuable for working toward sustainable systems, they are insufficient to create a comprehensive sustainability strategy. Aspects of design and operation of the facility must also be considered and incorporated. Within a facility logistics context, however, sustainability issues have received little attention, although related logistics areas have been more thoroughly explored. These areas include reducing emissions and other environmental costs through optimization of transportation and distribution, development and use of closed-loop supply chains, and the creation of the LEED certification system for facilities. We will discuss these areas in greater detail due to the connection to facility logistics and the need to understand integrated approaches.

2.1 Green Supply Chain Management and Operations

2.1.1 Environmental Impact of Transportation

2.1.2 Closed Loop Supply Chain

Early product designs were often inefficient over the total product life cycle from using too much material to require too much energy for operation to being difficult to repair, reuse, or reclaim the material contained in the product. Manufacturers have changed greatly by developing designs that avoid environmentally hazardous materials and make it easier to reuse the product at the end of its life cycle. A prime example is the use of modular designs to facilitate component part replacement by users and repair and remanufacturing by original manufacturers and/or third parties [19].

To exploit these product designs for remanufacturing and reuse, reverse supply chains were developed to acquire used products, move those products to reprocessing facilities, inspect them to determine whether and how to repair, remanufacture, use for spare parts, recycle, or dispose, remanufacture the product, and then distribute the remanufacturing product back into the marketplace [20]. Many examples focused primarily on recovery and recycling, e.g., the case study and solution approached described in [21]. Take back legislation also drives the development of closed-loop supply chains [22, 23]. The concurrent design of a product and the corresponding return supply chain is described in [24]. However, forward and reverse supply chains form a closed loop when they are managed in a coordinated way toward the common goal of maximizing profits [25]. There are considerable challenges in designing and managing these closed-loop systems, and there has been considerable research addressing these issues. An overview and good list of references is provided by [20]. Also, for an older but broader view, [26] provides a survey of environmentally conscious manufacturing and product recovery and includes an extensive list of references.

Of course, closed-loop supply chains have many implications for facility logistics. The design and operation of the receiving, inspection, and disposition areas is critical. These operations can be challenging due to the varying nature, condition, and containerization, if any, of the products being received. Unlike a forward distribution center, where the size, type, and condition of the unit loads to be handled is known and consistent, the closed-loop system must anticipate and deal with more uncertainty and thus flexible and adaptable configurations are required and manual or mechanized handling is often critical.

2.1.2 Green Manufacturing and Distribution

Sustainability is described by [27] as including environmental management, closed-loop supply chains, and a broad perspective on triple-bottom-line thinking — integrating profit, people, and the planet into the culture, strategy, and operations of companies. While this is a broad description, many initiatives have focused on green manufacturing and green logistics.

For example, Toyota's environmental commitment [28] extends through the full life cycle of their products - from design to production through use and disposal. To reduce waste in manufacturing plants and processes, Toyota uses the 5Rs: refine, reduce, reuse, recycle, and recover energy. Toyota has reduced water usage by changing production processes and greatly reduced landfill waste by changing packaging and containers, e.g., using metal reusable containers instead of cardboard and wood pallets, and by extensive recycling programs. They are evaluating new materials for use in their vehicles and have programs focused on eliminating toxic or potentially concerning substances. They are also working to increase the end-of-life vehicle recovery rate with a goal of 95% by 2015. Large companies, like Toyota, can work on many aspects across the product's life cycle and across many phases of the manufacturing, distribution, and use.

The concept of lean manufacturing supports sustainable manufacturing. Lean seeks to eliminate wastes that impact traditional production objectives like cost or time but can also be used to help eliminate wastes that impact the environment [29]. Eliminating waste from overproduction or excess transportation also has positive, if secondary, impacts on the environment. Using lean techniques to focus explicitly on reducing additional environmental wastes can further improve sustainability.

Capacity planning decisions are aimed at providing the right amount of capacity at the right place and at the right time. Obviously, capacity planning impacts the environment in several direct and indirect ways. Choosing environmental friendly resources and right-sizing those resources are important. Considering the energy use, material consumption, and waste production of various capacity planning and scheduling solutions along with the fixed and variable costs is more challenging but just as important. Environmental guidelines, such as, allocating right equipment for each task, reducing setup operations, avoiding reheating or restarting processes, and avoiding accumulation of hazardous materials, should be considered. However, these guidelines only provide an ad-hoc means of addressing the issues. Production planning models that explicitly consider these issues are needed but are far from comprehensive.

For example, [30] develops an environment-oriented production planning model that compares a reactive model, where maximum emission standards set by legislation are just met and additional environmental investments are made only if they increase profit, versus a proactive model, where pollution emissions are minimized subject to a certain minimum profit level being achieved. Of course, in both models but especially in the proactive one, a system of weights that specifies the different degrees of harm of each pollutant is necessary and the solution is sensitive to the specification of these weights. However, [30] found that under certain reasonable scenarios, the emissions could be greatly reduced without correspondingly large sacrifices in profit. Additionally, they demonstrated how it might be possible to use dual prices as a surrogate weight to balance the competing objectives. Along a similar line, [31] developed aggregate planning models for products to be recovered at end of life.

2.2 LEED Certification System

The LEED green building certification program [32] is an internationally recognized system for providing third-party verification that a building or community was designed and built using strategies aimed at improving performance across a variety of metrics related to energy use and environmental stewardship, including energy savings, water efficiency, CO₂ emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts.

LEED is an acronym that stands for Leadership in Energy and Environmental Design, which was developed by the U.S. Green Building Council in 2000. LEED provides a framework for identifying and implementing practical and measurable green building design, construction, operations, and maintenance solutions. This framework is primarily

aimed at architectural and construction features and issues, but design and operation from a facility logistics viewpoint impacts and is impact by these issues.

LEED certification is available for all building types including both new construction and major renovations. LEED is a point-based system where building projects earn LEED points for satisfying specific green building criteria [33]. Within each of the LEED credit categories, projects must satisfy particular requirements to earn points. The five categories include sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality. A scorecard is developed to determine the number of points in each category.

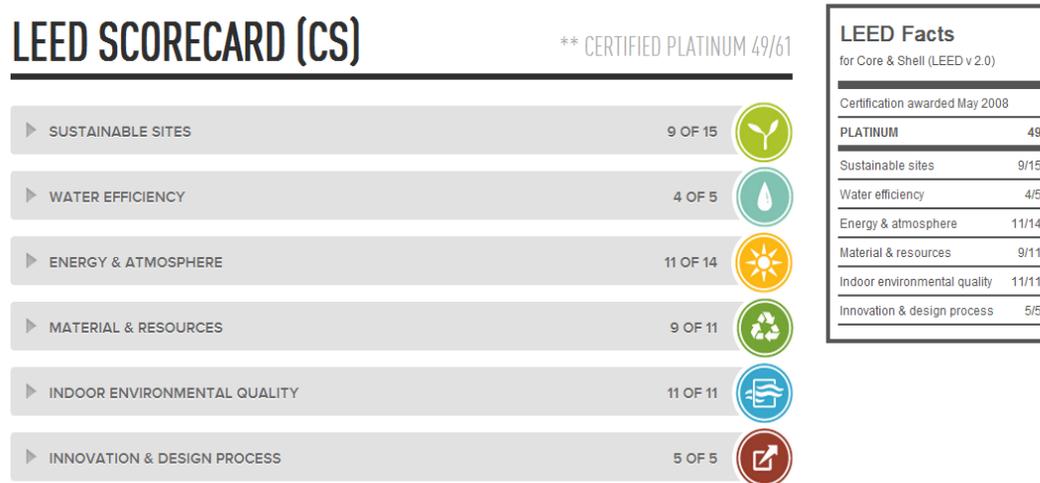


Figure 1. LEED Scorecard (U.S. GBC)

The number of points the project earns determines the level of LEED Certification the project receives. LEED certification is available in four levels according to the following scale:

- Certified 40–49 points
- Silver 50–59 points
- Gold 60–79 points
- Platinum 80 points and above

LEED-certified buildings are designed to [33]:

- Lower operating costs and increase asset value
- Reduce waste sent to landfills
- Conserve energy and water
- Be healthier and safe for occupants
- Reduce harmful greenhouse gas emissions
- Quality for tax rebates, zoning allowances and other incentives
- Demonstrate leadership, innovation, environmental stewardship, and social responsibility

2.3 Summary of Previous Work

The breadth of sustainability issues and initiatives is tremendous. As stated in [34], “those practices that contribute to the enhancement of environmental performance in companies’ operations; involving practices for production planning, product and process development, supply chain management, production and finally after-sales operations” must all be considered. It is challenging to fully evaluate the impact of these efforts across the full life cycle of the products and the full scope of the system. Many initiatives have positive impacts in a particular area but may have negative impacts on the broader system or may have unintended consequences elsewhere. A comprehensive assessment method is critically needed but extremely challenging to develop.

From a facility logistics viewpoint, there has been work related to logistics, transportation, and supply chain but much less that focused within the facility, whether production or distribution. Of course, individual components or equipment has been improved to reduce energy consumption, eliminate environmental hazards, or otherwise increase the sustainability. However, explicitly incorporating sustainability issues into the design and operational decisions has received less attention.

3 Modeling Issues in Logistics and Facility Logistics

The lack of research focus on sustainability issues in facility logistics is likely due to three reasons. First, the impact of layout design, material handling, and operational planning decisions on the overall system is often indirect and difficult to assess. Second, from a conceptual standpoint, including sustainability issues in existing models is relatively straightforward. The challenge is in measuring the various factors, determining the appropriate cost coefficients, and setting the permissible limits. Third, these issues, particularly determining costs and limits, are often very problem-specific, thus making it difficult to develop generally applicable models or approaches.

In general, incorporating sustainability issues into any logistics system design decision is very complicated because of the multitude of interconnected decisions with consequences that may be difficult to predict or assess. Tradeoffs between the size and weight of the product, type and composition of packaging, distance traveled, mode of transportation, temperature/humidity control requirements, required response/delivery time, etc. all present tradeoffs that are difficult to balance.

Some specific tradeoffs are identified below. Note that these generally focus only on one issue but, even with that restriction, assessing the impact on the overall system or making the best decision is difficult.

3.1 Qualitative Illustration of Tradeoff Considerations

One of the basic decisions in logistics, facility location, is being greatly impacted by sustainability issues. The environmental impact of transportation within the logistics system is being explicitly considered. The cost of production and distribution, the delivery or response time, and the environmental impact of the transportation must all be optimized to determine the best locations for production and distribution facilities. Companies are rethinking where they location facilities and the site with the least expensive labor no longer always wins. These changes are also driving companies toward more distributed production to reduce the transportation costs and environmental impact, but balancing the tradeoffs between production economies, transportation costs, and environmental issues is challenging, even from this relatively simple problem.

A basic decision within facility logistics involves the determination of the transfer batch size. The fundamental tradeoff between efficiency of material handling and the impact on work-in-process inventory levels and cycle time is of primary concern. When sustainability impacts are considered, a new set of issues arises. The efficiency tradeoff still exists but not must consider the environmental impact of the number of material handling trips, not just the direct operational costs. Also, the size of the transfer batch affects the type of material handling equipment to be used. The choice of equipment impacts not only the fixed and variable costs but also the initial and subsequent environment impacts from production, use, and disposal of the equipment. If the environmental costs are large or the environmental impact is weighted heavily, then the design decision may trend toward smaller unit loads with more manual handling, perhaps reinforcing the production ideal of one-piece flow.

A fundamental decision in warehousing and distribution is the configuration of the storage space in three dimensions. Classic tradeoffs of reduced footprint versus increased costs per square foot must be augmented with other considerations. The impact of building height on the heating, cooling, and lighting requirements in the facility must be considered. The different material requirements, e.g., concrete, steel, etc., for the building and the storage racks in each configuration should be addressed from an environmental perspective. As an aside, assessing the environmental impact of the use of concrete from production through use and to disposal is quite an undertaking.

Equipment selection decisions, in isolation, are also greatly complicating by sustainability issues. The initial cost, the environmental impact of producing the equipment, the operating cost, the environmental impact during use, and the environmental impact at end-of-life should all be considered and balanced. Clearly, assessing these costs or impacts and making the appropriate tradeoffs are difficult even without consider the influence of the equipment selection on the larger system.

Making strategic choices is always challenging and usually influenced greatly by past experience. However, considering environmental impacts are critical to creating sustainable solutions. These choices arise at both the logistics and facility levels. Choices, such as centralized versus decentralized facilities or storage, the amount of

inventory to hold and the locations of this inventory, will have many ripple effects through the system design. Operational strategies, e.g., part-to-picker versus picker-to-part order picking, are also impacted by environmental concerns. Providing modular, flexible designs to adapt to changing requirements and extend the useful life of the facility without major changes can clearly create improvements in sustainability but perhaps at the expense of other objective measures. Finding the best balance of automated, mechanized, and manual handling activities is affected and may point to differing types of solution approaches.

From one aspect, some operational issues can be addressed somewhat independently. The basic approach here is to “do what you are already doing more efficiently.” Industrial assessment techniques to improve energy efficiency, reduce energy consumption, or capture and reuse waste can be directly applied. Unintended consequences of this type of myopic approach can arise and ultimately a more comprehensive, systemic methodology is needed.

Design issues, alternatively, are very difficult to scope. Where do you draw the boundaries for assessing the impact of the system? New or revived concepts may be necessary to achieve significant improvements. True modularity to enhance efficiency and allow expandability may become a renewed goal. Capturing the “costs” or otherwise weighting different factors to make tradeoffs is challenging but critical. Considering the operational performance, in terms of traditional profitability-related measures and new sustainability-related measures, is needed to evaluate designs. Being about the “simulate” performance thus takes on an entirely new and expanded meaning.

3.2 Sample Modeling Process

As an example, we consider the operational issue of production planning and demonstrate how it is associated with green and sustainable operations. The model aims to establish a tradeoff between economic and environmental objectives using a conceptually straightforward approach. Within a facility logistics context, this problem is well defined in that the system and available resources are given and the attributes of the production processes required for each product are known. In the broader context, each of these design decisions would be part of a complete system model.

The production-planning model maximizes the profit while considering environmental aspects along the supply chain. In this sample model, some environmental aspects are considered as constraints and some are considered as costs that are part of the objective function.

The example model is based on a production process with the following features:

- The company produces several products on different machines. Each machine or process has different environmental impacts.
- Jobs can be assigned to different machines with different cost, time, and environmental factors.

- The market demand for the products, the capacity of each machine, and the process requirements for each job on each machine are certain and known.
- The cost, energy use, and waste produced by each machine in processing each job are known but vary according to the job-machine combination.

To incorporate sustainability issues, the environmental factors to be included in the model must be identified and measures for those factors must be determined. There are a variety of potential factors to be included but generally environmental measures or wastes are considered. Environmental wastes can occur with use of resources or release of substances to air, water, or land that could be considered harmful to human health or the environment. Environmental wastes can occur when companies use resources to provide products or services to customers and when customers use and dispose of products.

Practically speaking, environmental wastes include [35]:

- Energy, water, or raw materials consumed in production, distribution, and use.
- Pollutants and material wastes released into the environment, such as air emissions, wastewater discharges, hazardous waste, and solid waste.
- Hazardous substances that adversely affect human health or the environment during their use in production or their presence in products.

From [36], the factors in Table 1 are identified and defined.

Table 1. Categories, Definitions, and Measures of Environmental Wastes [36]

<i>Category</i>	<i>Definition</i>	<i>Metric</i>	<i>Units</i>
Energy Use	Any source providing usable power or consuming electricity Transportation and non-transportation sources	Energy Used	Specific to energy source such as BTUs or kilowatt hours % reduction, energy use/unit of product
Solid Waste	Wastes other than RCRA hazardous wastes.	Solid (Non-Hazardous) Waste Generated	Pounds/time % reduction or % recycled

Water Pollution (Liquid Waste)	Quantity of pollutant in discharged wastewater, includes: <ul style="list-style-type: none"> • Heavy Metals, e.g., lead, hexavalent chromium • Organic Pollutants and Pesticides • Conventional Pollutants, e.g., oil and grease • Nutrients, e.g., phosphur • Pathogens • Sediment from runoff Wastewater discharge volume	Mass or Concentration of Regulated Pollutants Discharged	mg/L % reduction
Air Emissions (Gaseous Waste)	Release of any of the following: <ul style="list-style-type: none"> • Air toxics - CAA 112b HAPs • Carbon Monoxide • Lead • Ozone and its precursors, including: <ul style="list-style-type: none"> ◦ VOCs (volatile organic compounds) ◦ NOx (nitrogen oxides) • Ozone-depleting substances • PM10 (particulate matter) • PM2.5 (fine particulate matter) • Sulfur Dioxide • Greenhouse Gases, including CO₂ 	Air Emissions Generated	Tons/year % reduction

In order to identify the possible harmful effects to the environment due to the production of certain products all the different impacts in every stage of the life of the product should be considered. One approach for determining these impacts is Life Cycle Assessment (LCA). LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service by compiling an inventory of relevant energy and material inputs and environmental releases and evaluating the potential environmental impacts associated with identified inputs and releases [37]. Life cycle assessment is a “cradle-to-grave” approach that evaluates all stages of a product’s life from the perspective that they are interdependent. Figure 2 illustrates this view.

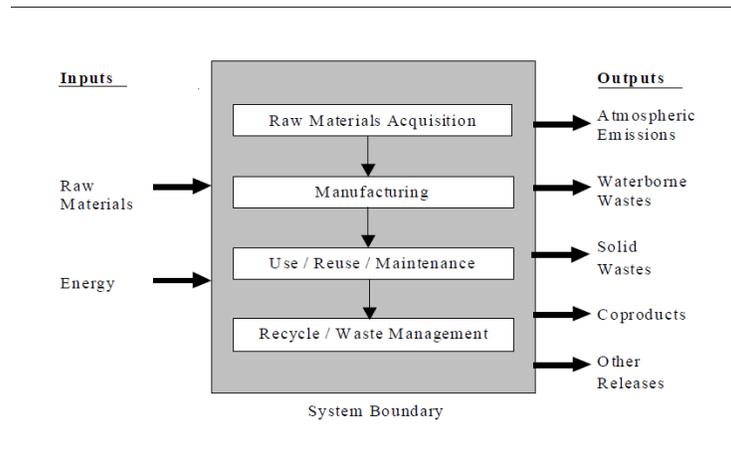


Figure 2. Life Cycle Stages (U.S. EPA)

Additionally, the International Organization for Standardization (ISO) uses life cycle assessment for “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” as part of its ISO 14000 standard and certification process [38].

By completing this type of assessment, the factors and measures can be identified. For our example, we will assume that we have the following variables and parameters to consider. In this sample problem, we will only consider the three types of waste: solid, liquid, and gaseous. In general, individual substances within each waste stream might be measured and treated separately.

Variables and Parameters

- x_{ij} is the number of units of product i ($= 1, \dots, n$) produced by machine j ($= 1, \dots, m$)
- r_i is the revenue (\$) per unit of product i
- c_{ij} is the variable cost (\$) of producing a unit of product i on machine j
- p_{ij} is the production capacity needed to produce a unit of product i on machine j
- P_j is the maximum production capacity of each machine j
- D_i is the maximum market demand for each product i
- w_{ij}^s (w_{ij}^l, w_{ij}^g) is the amount of solid (liquid, gaseous) waste generated in producing product i on machine j
- W_s (W_l, W_g) is the maximum permission amount of solid (liquid, gaseous) waste
- t_{ij} is the time required to produce a unit of product i on machine j
- o_j is the power consumption of machine j during processing (KWhr)
- ξ is the cost per under of power consumed (\$/KWhr)

Given these variables and parameters, we can develop a base formulation for the production planning model. The objective function will have the same requirements as traditional production models and will attempt to maximize the profit considering the revenue generated, the variable production costs, and the energy consumption costs.

$$\text{Maximize } \sum_{i=1}^n \sum_{j=1}^m r_i x_{ij} - c_{ij} x_{ij} - t_{ij} x_{ij} o_j \xi$$

Several constraints are included in the formulation. Traditional capacity and demand constraints are used. In addition, there are constraints limited the amount of waste produced. In this type of model, the waste streams are defined as constraints with limits set either by regulation or by company policy. The right-hand side of these constraints can be used in sensitivity analysis and dual-prices can be determined to identify the value of changing these limits to the overall solution. Of course, Lagrangean approaches can also be used to incorporate these constraints into the objective function. An alternative formulation, not presented here, would explicitly model these waste streams as cost factors and incorporate them directly into the objective.

Subject to:

$$\begin{aligned} \sum_{i=1}^n p_{ij} x_{ij} &\leq P_j & j = 1, \dots, m \\ \sum_{j=1}^m x_{ij} &\leq D_i & i = 1, \dots, n \\ \sum_{i=1}^n \sum_{j=1}^m w_{ij}^k x_{ij} &\leq W_k & k = s, l, g \end{aligned}$$

The formulation is straightforward and is a conceptual extension of basic production planning models. More complicated versions and additional restrictions can be included. The challenge, from a practical perspective, is in measuring w_{ij}^k values and in determining the W_k limits. Additionally, the values for o_j may vary depending on other operating parameters, e.g., what happens when the machine is idle, what happens during setup, is the machine kept running or shut-down, how much power is consumed, all impact the solution. It is these items that limit the applicability of current modeling approaches.

4 Summary

Discussion of environmental issues and concern for lessening human impact on the environment in the face of continued growth and prosperity as a world economy appears to be increasing. Consensus over the true impact of human activities and how to mitigate those has yet to be reached. However, individuals, companies, and governments are increasingly looking for ways to identify and deploy sustainable solutions. These sustainability efforts primarily revolve around reducing energy consumption, particularly

that ultimately derived from oil, reducing air and water emissions, and decreasing the consumption or desecration of natural resources.

For logistics systems, these issues have driven change in the design of products, the nature of manufacturing processes, and the strategies for designing and operating facilities and systems. Most closely related to facility logistics are the development of reverse logistics and closed loop supply chains to aid in the reclamation and reuse of products and the specification of standards for building design that reduce the environmental impact and improve the facility's performance.

4.1 Future Work

From a research perspective, sustainability issues in facility logistics presents several dilemmas. Previously, three factors were cited as possible explanations for the relative lack of research focus on sustainability issues in facility logistics: the impact on the overall system is often indirect and difficult to assess; conceptually, including sustainability issues in existing models is relatively straightforward; measuring the various factors, determining the appropriate cost coefficients, and setting the permissible limits is the primary challenge but these are often very problem-specific.

Thus, from a practical perspective, methods to determine the critical environmental factors and measure and assess their impact are needed. Using benchmarking techniques and drawing modeling approaches from macroeconomics might be useful in this regard. Interesting research avenues also exist with respect to determining methods for making decisions with missing and uncertain data. It is highly unlikely that we will be able to understand all of the consequences and gather accurate data to assess all of the factors. How can we make good decisions in the midst of this uncertainty? What portions of the problem are critical to model and how do we assess those? Tools and techniques adapted from systems engineering may be useful here. Simulation methods are needed for assessment and evaluation. These methods likely will not be precise discrete-event models but will need to account for and embrace the lack of data and the considerable uncertainty. Again, a tie to economics may be useful here. Developing or adapting techniques for experimentation and sensitive analysis on a large scale and with lack of precise inputs is another area for potential exploration.

One of the major challenges for this area, though, is determining the scope of the system of interest. What system boundaries will provide good solutions while making the problem solvable? Which factors must be explicitly addressed, which can be aggregated, which should be ignored? How do you anticipate potential consequences and how do you determine which to explicitly model? Defining the nature and scope of the system has long been a challenge of engineering design and analysis but it becomes even more so when sustainability issues are included. Decomposition approaches, which often work well in complicated system design situations, may be problematic when environmental issues, which tend to have large ripple effects, are included. At a minimum, clear interfaces to retain and describe the interdependency between the

components is required. New approaches that seek to retain critical problem aspects while reducing other less critical ones likely need to be developed.

While there are some focused problems that arise in the context of sustainable systems, e.g., how to efficiently handle receiving in a remanufacturing facility that is part of a closed loop supply chain, these broader issues are sources for having a large impact on practice. Determining good approaches for defining the system, identifying the key issues, and assessing the impact of alternatives is critically needed.

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