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AN EVENT-LOG ANALYSIS AND SIMULATION-BASED APPROACH FOR QUANTIFYING SUSTAINABILITY METRICS IN PRODUCTION FACILITIES

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ABSTRACT

This paper describes a discrete-event simulation and event-log analysis based approach for computing sustainability metrics in production environments to perform various types of comparative analysis and assessments. Event logs collected from the production environment are analyzed to compute current state sustainability metrics such as energy usage, carbon footprint and heating/cooling requirements. Bootstrapping based forecasting leveraging expert input is utilized to estimate future demand. The forecasted demand is then simulated to predict sustainability metrics. The discrete-event simulation results from the forecasted data and computation of heat produced is combined with thermodynamic models of heat transfer through the thermal envelope of the facility to provide more accurate estimates of true carbon footprint associated with the production operations while also enabling cross-comparative studies of setting operations in different geographical locations. The framework and software tool enables the integration of productivity metrics and sustainability metrics in decision-making process for designing and operating production environments.

1 INTRODUCTION

Production environments consisting of people and devices consume energy and have an impact on the environment. Often times, green metrics such as carbon footprint of the operation which depends on the details of the operating conditions is ignored or incorrectly estimated in planning, location and design of these facilities. In this paper, we will describe a discrete-event simulation-based approach to the computation of green metrics that will aid in performing a sustainability analysis of the operation and also enable a more quantitative comparison of various scenarios based on those metrics in addition to the productivity metrics. The green metrics of interest to us are heat output, air-conditioning requirements and carbon footprint both in an aggregated form as well as time-dependent view.

Production environments experience varying loads and operating conditions, depending on the type and state (idle/busy) of the machines, labor staffing levels and scheduling policies (i.e. what machines are working on what jobs). These environments consume energy and generate heat. If the objective is to evaluate what the carbon footprint of the facility is, just knowing the energy characteristics of the machines in the absence of how they are utilized and operated upon in the production environment is likely to give an incorrect view of the green metrics of the shop.

In many instances, decisions made with respect to location of the facility also do not take into account what type of energy source (e.g. coal, nuclear, gasoline-powered generator) is being utilized in the region to generate power for the devices. Thus the significant variations in the carbon footprint associated with setting up the same operations in different geographical areas may not be quantitatively reflected in the decision-making process. With increased focus on environmental impact, there is increased emphasis on being able to quantify these metrics and include them in the decision-making process.

Many factors go into the accurate estimation of green metrics associated with the production facility such as demand volume and mix, energy characteristics of the equipment, type of energy source used to generate electricity, scheduling policies, labor staffing levels as well as the location of the site that drives the thermodynamic heat transfer between environment and facility.

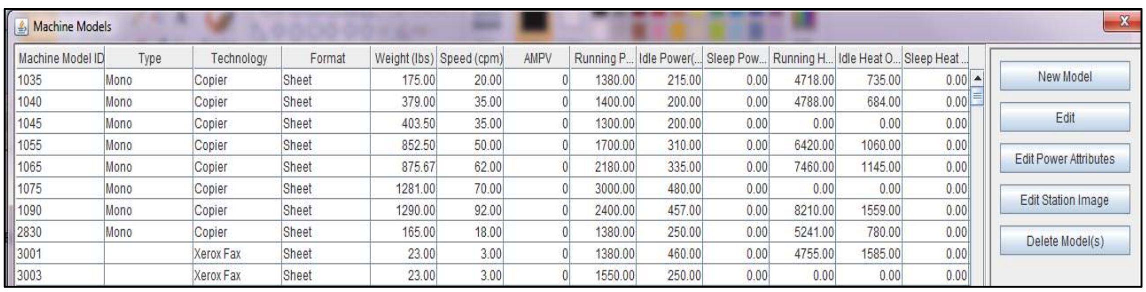
This paper will describe a discrete-event simulation framework that has been developed to estimate green metrics and enable the user to perform cross-comparative studies associated with designing and operating production environments. The focus domain for exemplification of these ideas is the print production environment where documents are manufactured but it will be readily obvious to the user that the approach can be extended for any manufacturing or service environment provided the relevant data can be captured. The discrete-event simulation approach with the corresponding inputs/outputs and workflow modeling approaches described in this paper has been implemented within Xerox's Lean Document Production (LDP) suite as extensions to its capabilities that were described earlier in Rai et al. (2009).

This paper is organized as follows. In Section 2, we will describe the data that was gathered to support the development of this framework. Section 3 describes the approach for computing the various green metrics. Section 4 describes the incorporation of thermodynamic models for heat transfer between the environment and facility into the analysis. Section 5 concludes the paper.

2 DATA FOR THE DEVELOPMENT OF THE SUSTAINABILITY METRICS COMPUTATION FRAMEWORK

The simulation-based framework for computing sustainability metrics requires two types of data. A static dataset that consists of equipment, characterization of the power source and people characteristics and a dynamic dataset that describes how the equipment and people are operating within the environment.

Figure 1 shows an example of a table that captures various equipment characteristics associated with various types of equipment. From a sustainability metric computation standpoint, characteristics such as power usage and heat generation when in equipment is in idle, sleep and running mode are key.


Machine Models

Machine Model ID	Type	Technology	Format	Weight (lbs)	Speed (cpm)	AMPV	Running P...	Idle Power(...	Sleep Pow...	Running H...	Idle Heat O...	Sleep Heat ...
1035	Mono	Copier	Sheet	175.00	20.00	0	1380.00	215.00	0.00	4718.00	735.00	0.00
1040	Mono	Copier	Sheet	379.00	35.00	0	1400.00	200.00	0.00	4788.00	684.00	0.00
1045	Mono	Copier	Sheet	403.50	35.00	0	1300.00	200.00	0.00	0.00	0.00	0.00
1055	Mono	Copier	Sheet	852.50	50.00	0	1700.00	310.00	0.00	6420.00	1060.00	0.00
1065	Mono	Copier	Sheet	875.67	62.00	0	2180.00	335.00	0.00	7460.00	1145.00	0.00
1075	Mono	Copier	Sheet	1281.00	70.00	0	3000.00	480.00	0.00	0.00	0.00	0.00
1090	Mono	Copier	Sheet	1290.00	92.00	0	2400.00	457.00	0.00	8210.00	1559.00	0.00
2830	Mono	Copier	Sheet	165.00	18.00	0	1380.00	250.00	0.00	5241.00	780.00	0.00
3001		Xerox Fax	Sheet	23.00	3.00	0	1380.00	460.00	0.00	4755.00	1585.00	0.00
3003		Xerox Fax	Sheet	23.00	3.00	0	1550.00	250.00	0.00	0.00	0.00	0.00

Figure 1: Equipment characteristics for computing sustainability metrics from simulation.

Figure 2 shows the information related to the CO_2 emission rate by country that is captured within the system. In this example, note that Uruguay's CO_2 Emission Rate is 102.74 grams CO_2 per Kilowatt hour.

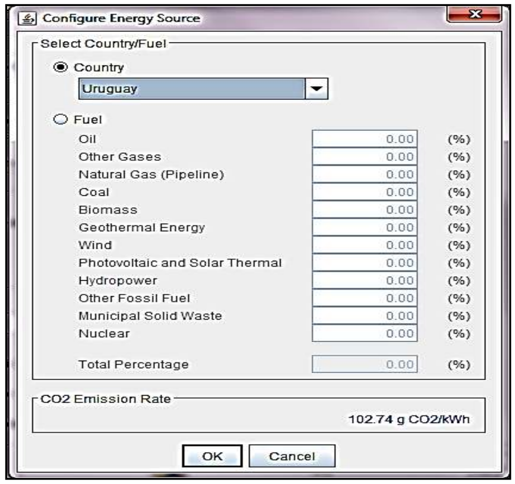


Figure 2: Illustration showing the CO2 emission rate by country as captured in the database.

Other types of static data that are captured define the characteristics of the specific production environment, such as number and types of equipment in the shop, the capabilities of the equipment in terms of the specific functions they can perform and human labor characteristics (such as their skill sets, schedules).

With respect to the (dynamically changing) job data, the system captures event logs associated with job execution on various devices as shown in Figure 3. The logs describe the arrival time of the jobs, the due date/time, the timestamp associated with when the job was started on a particular machine and timestamp associated with when it finished processing on the machine. Event logs associated with job interruption time, restart time are also captured. The name of operator and machine name associated with each event is also collected.

Job Event List

JobID	Station	Event	Operator	Timestamp	Quantity
35	TimeStamp	Arrival	Arrival	Jan 13, 2004 3:15:50 PM	0
35	TimeStamp	Due	Due	Jan 15, 2004 3:15:50 PM	0
35	BWPrinter2	Start	John	Jan 13, 2004 3:40:08 PM	23486
35	BWPrinter2	Interrupt	John	Jan 13, 2004 4:30:00 PM	7065
35	BWPrinter2	Restart	John	Jan 14, 2004 8:30:00 AM	16421
35	BWPrinter2	Stop	John	Jan 14, 2004 10:25:55 AM	16421
35	Inserter1	Start	Jeff	Jan 14, 2004 10:48:09 AM	16518
35	Inserter1	Interrupt	Jeff	Jan 14, 2004 4:30:00 PM	15259
35	Inserter1	Restart	Jeff	Jan 15, 2004 8:30:00 AM	1259
35	Inserter1	Stop	Jeff	Jan 15, 2004 8:58:13 AM	1259
35	Inserter1	Completed	Jeff	Jan 15, 2004 8:58:22 AM	1259
36	TimeStamp	Arrival	Arrival	Jan 13, 2004 3:23:30 PM	0
36	TimeStamp	Due	Due	Jan 15, 2004 3:23:30 PM	0
36	ColorPrinter1	Start	Mary	Jan 13, 2004 3:36:03 PM	7984
36	ColorPrinter1	Interrupt	Mary	Jan 13, 2004 4:30:00 PM	1776
36	ColorPrinter1	Restart	Mary	Jan 14, 2004 8:30:00 AM	6208
36	ColorPrinter1	Stop	Mary	Jan 14, 2004 11:38:34 AM	6208
36	MailStation1	Start	Brett	Jan 14, 2004 11:54:14 AM	291
36	MailStation1	Stop	Brett	Jan 14, 2004 12:55:24 PM	291
36	MailStation1	Completed	Brett	Jan 14, 2004 12:55:33 PM	291

Figure 3: Event logs associated with the flow of each job through the facility.

3 COMPUTATION OF SUSTAINABILITY THROUGH PROCESS LOG MINING OF RAW AND SIMULATION-GENERATED DATA

The event logs give a view into when each machine and operator was busy. Combining this with the operational characteristics of the machines and the energy source associated with the place where the shop is located can give an accurate view into various green metrics. The approach parses through the log along the timeline and aggregates the heat and power usage metrics by machines.

The first step to calculation of the actual energy usage of the print center is to split its consumption into both steady state and variable components. The steady state energy usage can be calculated through an understanding of the power consumed in the condition where no work exists for the print shop. Each piece of equipment in the shop can be described as existing in one of the states of "running", "idle", or "sleep". In the condition where no work exists for the shop, only the states of "idle" and "sleep" contribute to the shop's power consumption. By examining the event log recorded for each piece of equipment in the simulation model, the system can calculate a "steady state" power usage of the shop by applying the "idle" power usage value to times where the machine is available in the shop and the "sleep" (or off) power usage value to times where it is unavailable. The sum of this consumption across all equipment describes the "steady state" power consumption of the print center. The power consumption is converted to the CO2 emission rate (Figure 2) to determine CO2 emissions resulting from power use at the print center.

This results in computation of green metrics reports associated with the production environment as shown in Figure 4. For more information refer Rai and Lambrecht (2013).

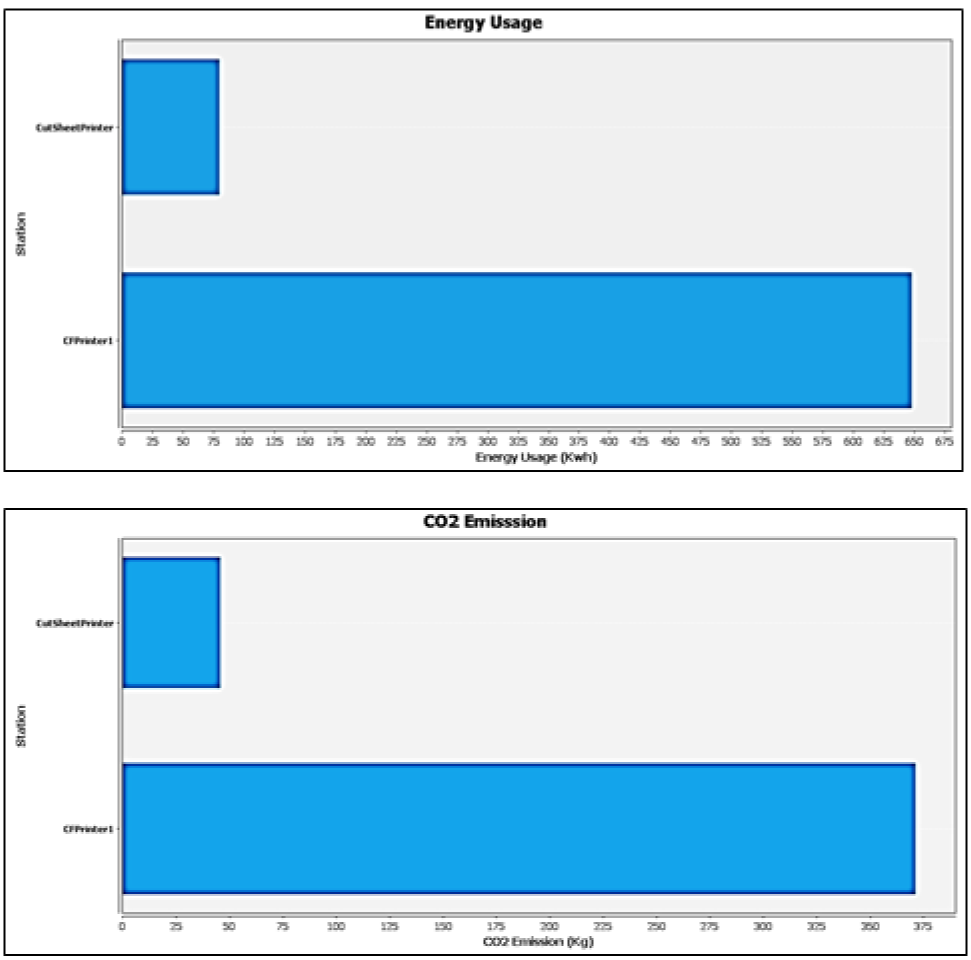


Figure 4: Reports showing green metrics computed from event logs.

3.1 Computation of green metrics in the context of print production environments

Heat is a by-product of print production, emitted from many sources within a print production facility. Heat is emitted from print and finishing equipment, lights, computers and other office devices, as well as from people. It is not uncommon for a large device such as a Xerox 650/1300 Continuous Feed Printer to emit more than 65,000 British Thermal Units (BTUs) per hour, which is equivalent to the capacity of a furnace in a 1750 square foot home in Rochester, NY. Even in stand-by mode, the Xerox iGen4 printer emits in excess of 30,000 BTUs. Light production machines such as the Xerox DocuTech 6155 emit about 20,000 BTUs when running and 3600 BTUs in idle mode, and there tend to be several in a production shop. Lighting is a known contributor to the heat emissions in a facility, where each fluorescent bulb gives off about 92 BTUs per hour. For purposes of estimating the effect of workers in a facility, 500 BTUs per person is typically used for air conditioning size calculations.

The performance of printing and finishing equipment is often strongly dependent on the operating environment. For example, a high-humidity environment can lead to excessive paper jams. Similarly, the print quality of many of these machines may degrade when temperature and humidity varies a great deal. This is more so in warmer climates. Print shops therefore take great care to invest in adequate air-conditioning capacity so that the production environment has the proper temperature and humidity to achieve optimal performance.

The heat generated as a by-product of print production is typically quantified only during establishment or upgrade of a facility's heating and cooling systems. These calculations are usually performed by a heating/cooling professional. During daily operations, heat emission is usually thought of as a necessary evil, countered by ventilation during cool seasons and by air conditioning in warm seasons. Examination of a facility's utility usage may provide clues as to the effects of the heat generated, but there is no convenient means of separating out the effects of the heat due to print production machinery. This information is important to management when considering consolidation or expansion of facility. If the information were more readily available, it would be useful when deliberating changes to the equipment mix, relocation to different locations, or when considering the outsourcing of work.

Large print shops (e.g. transaction environments) often utilize demand forecasts for planning workload. For example, a shop may use a random walk forecasting approach to determine the volume in the forthcoming months. In some cases, this is coupled with additional input from customers to determine how much work will be coming in the future (planning) time period. Figure 5 shows an example of a spreadsheet that shows how much volume is anticipated from different print shop customers in a transaction print shop.

Cycle	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5	Customer 6
05/01/10	0	0	0	1	0	0
05/02/10	0	72	27	0	356	63130
05/03/10	1078	44	22	24	2888	58463
05/04/10	0	0	0	91	0	0
05/05/10	0	0	0	32	0	0
05/06/10	0	0	0	4	0	0
05/07/10	1	205	152	19	67925	227813
05/08/10	0	0	0	36	0	0
05/09/10	0	144	78	0	17876	107077
05/10/10	0	115	80	4	28351	67444
05/11/10	0	297	194	3	443	58989

Figure 5: A spreadsheet showing how much volume is anticipated from different customers on different dates.

The volume information and estimation on job arrival times and job size distributions associated with different customers can also be bootstrapped to generate a job list describing each customer's demand. Bootstrapping is a self-sustaining, non-parametric, computationally intensive approach to statistical inference used to produce voluminous data. The idea of bootstrapping is to resample (with replacement) from the sample at hand randomly assuming the sample at hand as surrogate population (Efron 1979, Efron and Tibshirani 1993). Extensions of bootstrapping to a multi-product production demand forecasting are described in Rai and Ettam (2015).

A shop can be simulated with the forecasted dataset and an accurate representation on how a machine will operate in a future state can be determined. Figure 6 shows an example of how different pieces of equipment will be utilized in the future if the shop is run as per a pre-specified physical layout and scheduling policy configuration.

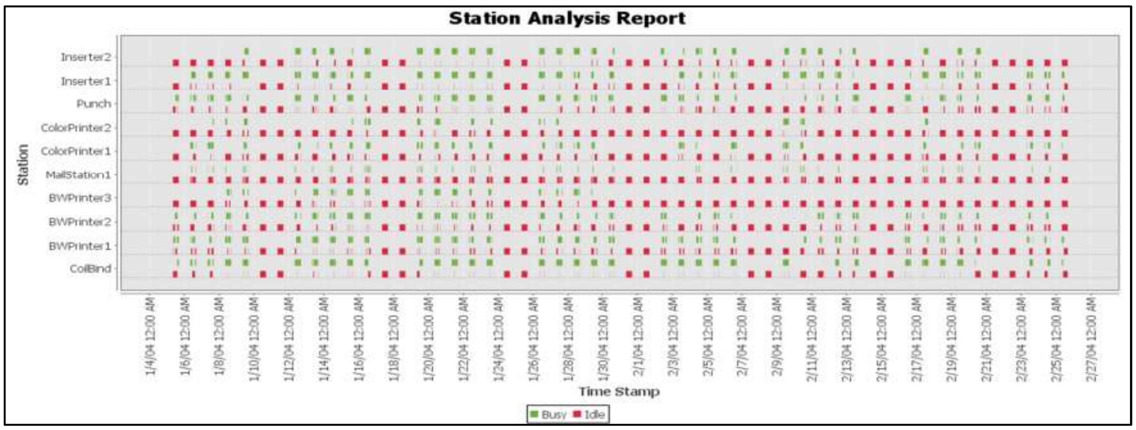


Figure 6: Simulation results showing the busy and idle/time in the future.

Since the heat emitted by different pieces of print production equipment is different whether it is busy or idling, the heat emission at any given time calculated using this approach will be significantly more accurate than the one where the maximum heat emission per equipment is used and added. The heat emitted by lights, computers and other office equipment, other significant heat sources, and office people employed in the shop at any given time can be added to the heat emitted by the equipment to calculate the total heat emitted in the production environment. The time varying heat emission is calculated using this approach. Figure 7 shows a schematic view of the heat emission plot as a function of time.

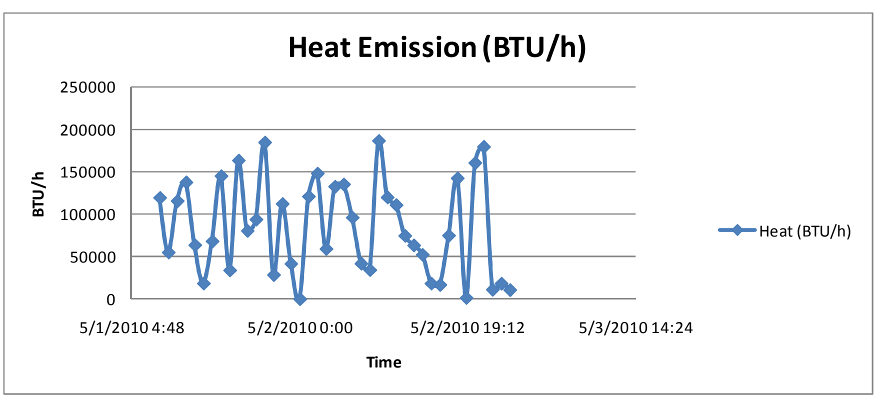


Figure 7: Heat emission from the production environment as a function of time as calculated from simulation of jobs taking into account specifics of when printer is idling or running.

4 INCORPORATION OF THERMODYNAMIC MODELS OF HEAT TRANSFER BETWEEN FACILITY AND ENVIRONMENT

The heat emission profile shown in Figure 7 can be used to determine effects on the heating and air-conditioning demands of the production facility as a function of time. This is accomplished by considering the location of the shop and its structural characteristics, then calculating the heat loss through the structure. The structural characteristics are used to develop a simple model of the thermal envelope of the facility. Historical temperature data is used to estimate the outside temperature, based upon the dates of the simulation. The thermodynamic formula for heat loss is then applied to determine whether the total heat emissions are beneficial, inexpensive to mitigate via ventilation, or expensive to mitigate via air conditioning.

During the heating season, if the total heat emission from a production facility is less than the total heating demands of a facilities space, the heat produced is beneficial. The amount of heat required by a building's furnaces is reduced by the amount of heat emitted within the facility. If the production equipment heat emission exceeds the heating demands, the facility's air handling ventilation system will mitigate the excessive heat, and no heat is required of a building's furnaces.

During the cooling season, a facility's air conditioning system must mitigate the excess heat. The amount of air conditioning required is a function of the facility's climate. On days where the facility's average outside temperature is > 65 degrees, air conditioning is normally required. Cooling Degree Days (CDD) is a measure of this. In a place such as Miami (See Figure 8), according to the 30 year historical data records from the National Oceanic and Atmospheric Administration (NOAA), every day has non-zero CDD, so air conditioning is required every day.

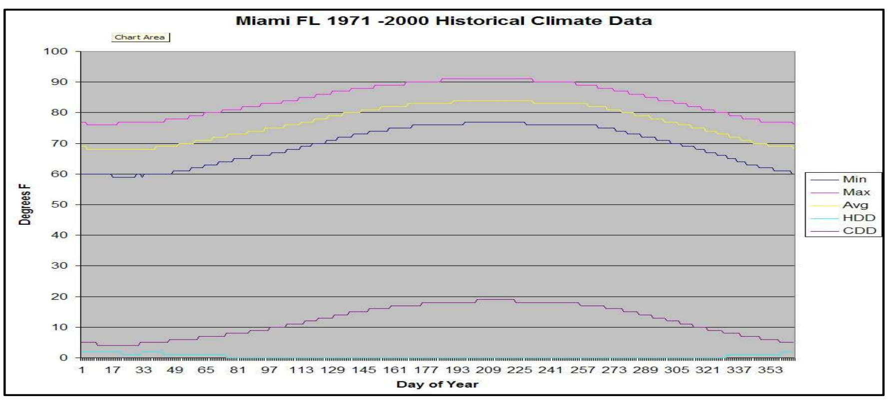


Figure 8: Historical climate data for Miami, FL.

In a place such as Minneapolis, Minnesota (see Figure 9), there are just 152 days per year with a non-zero CDD, so air conditioning is required only about 42% of the days in a year.

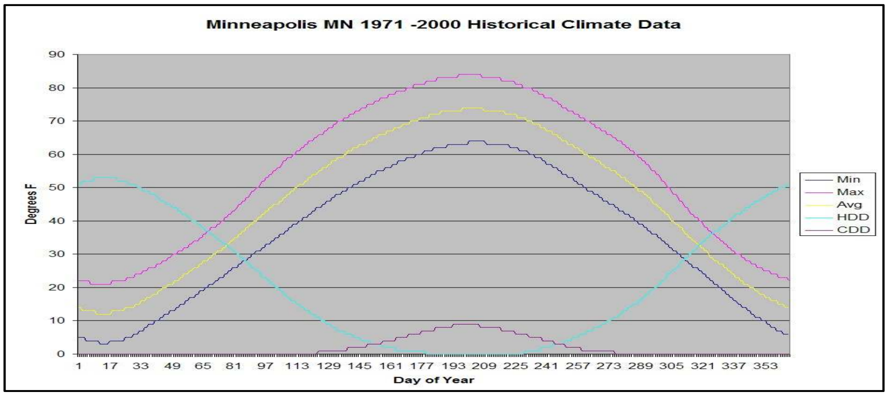


Figure 9: Historical climate data for Minneapolis, MN.

The location of a facility and the time of year that production is performed are therefore important factors when calculating a facility's carbon footprint. The aforementioned 30 year historical data records from NOAA are readily available for populated areas where production facilities are likely to be located. The thermal resistance values of a production facility are easily estimated, due to code regulations for commercial buildings. Figure 10 shows an example of such regulations obtained from https://www.energycodes.gov. The climate zones mentioned are shown in Figure 11.

TABLE 502.2(1)
BUILDING ENVELOPE REQUIREMENTS - OPAQUE ASSEMBLIES

CLIMATE ZONE	1		2		3		4 EXCEPT MARINE		5 AND MARINE 4		6		7		8	
	All other	Group R	All other	Group R	All other	Group R	All other	Group R	All other	Group R	All other	Group R	All other	Group R	All other	Group R
Roofs																
Insulation entirely above deck	R-15ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-20ci	R-25ci	R-25ci	R-25ci	R-25ci
Metal buildings (with R-5 thermal blocks[a, b])	R-19	R-19	R-13 + R-13	R-13 + R-13	R-13 + R-13	R-19	R-13 + R-13	R-19	R-13 + R-13	R-19	R-13 + R-19	R-19	R-13 + R-19	R-19 + R-10	R-11 + R-19	R-19 + R-10
Attic and other	R-30	R-38	R-38	R-38	R-38	R-38	R-38	R-38	R- 38	R-38	R-38	R-38	R-38	R-38	R-49	R-49
Walls, Above Grade																
Mass	NR	R-5.7ci[c]	R-5.7ci[c]	R-7.6ci	R-7.6ci	R-9.5ci	R-9.5ci	R-11.4ci	R-11.4ci	R-13.3 ci	R-13.3ci	R-15.2ci	R-15.2ci	R-15.2ci	R-25ci	R-25ci
Metal building[b]	R-16	R-16	R-16	R-16	R-19	R-19	R-19	R-19	R-13 + R-5.6ci	R-13 + R-5.6ci	R-13 + R-5.6ci	R-13 + R-5.6ci	R-19 + R-5.6ci	R-19 + R-5.6ci	R-19 + R-5.6ci	R-19 + R-5.6ci
Metal framed	R-13	R-13	R-13	R-13+ 7.5ci	R-13 + R-3.8ci	R-13 + R-7.5ci	R-13 + R-7.5	R-13 + R-7.5ci	R-13 + R-7.5 ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-7.5ci	R-13 + R-15.6ci	R-13 + R-7.5 ci	R-13 + R-18.8ci
Wood framed and other	R-13	R-13	R-13	R-13	R-13	R-13	R-13	R-13+ R-3.8ci	R-13 + R-3.8ci	R-13 + R-3.8	R-13 + R-7.5	R-13 + R-7.5	R-13+ R-7.5ci	R-13 +7.5ci	R-13 + R-15.6ci	R-13 + 15.6ci

Figure 10: Building envelope requirements.

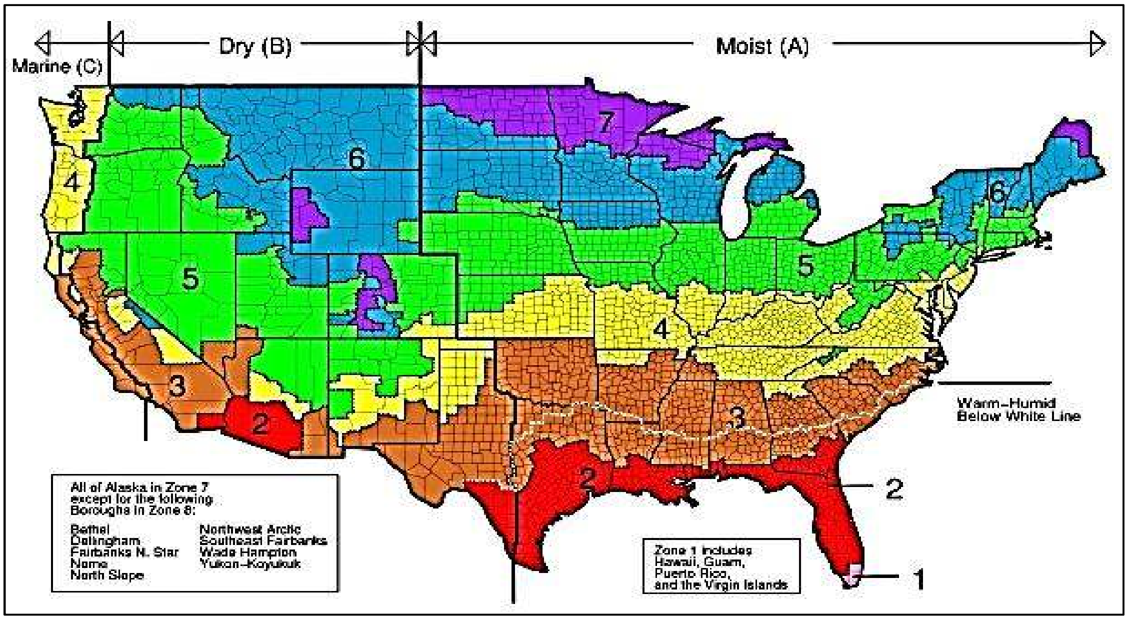


Figure 11: Climate zones in the continental US.

The only remaining information necessary to calculate a building's heat loss is the geometry of the building. The well-known thermal dynamics formula for heat loss (https://www.dli.mn.gov/CCLD/PDF/energy7678.pdf) can be used to calculate the amount of heat necessary to maintain a constant inside temperature:

$$P = \left({}^{A_1}/_{R_1} + {}^{A_2}/_{R_2} + \cdots + {}^{A_n}/_{R_n}\right) \times \Delta T$$

Where, P is the heat loss rate, A is the area of building with thermal resistance of R and ΔT is the temperature difference between the inside and outside temperatures assuming constant average indoor temperature.

By calculating the average P for a given day, a comparison to the points in Figure 7 yields whether each point falls into the beneficial, inexpensive-to-mitigate, or expensive-to-mitigate categories. This information can be aggregated to report the effects of heat generated as a by-product of production on a facility's carbon footprint. A line graph of the number of air conditioning tons necessary to mitigate the expensive-to-mitigate points can then be generated. Where air conditioning is necessary, the formula one Ton = 12,000 BTUs/Hr is utilized. The corresponding energy use can be converted to CO2 emissions using information supplied as shown in Figure 2.

For the jobs run in a shop in Minneapolis (Figure 12), the green dots represent the beneficial heat and the yellow dots represent the inexpensive-to-mitigate heat. Next, for the jobs run in a shop in Miami (Figure 13), where the blue dots represent the expensive-to-mitigate heat. Similarly, one can compute the air conditioning demand for the jobs run in a shop in Miami as shown in Figure 14.

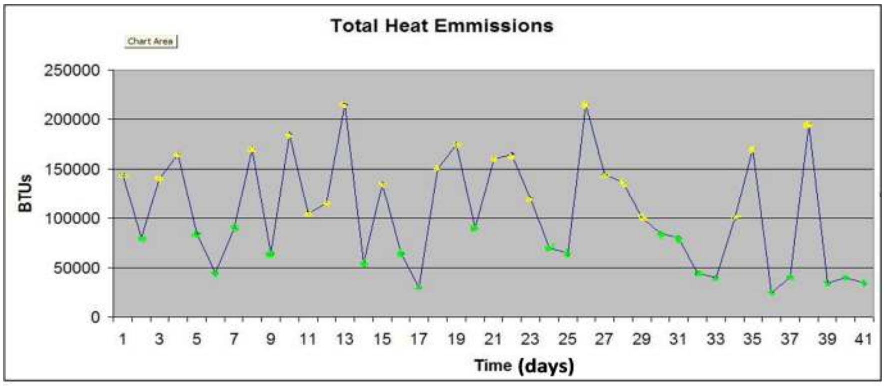


Figure 12: Heat emissions from a simulated shop in Minneapolis.

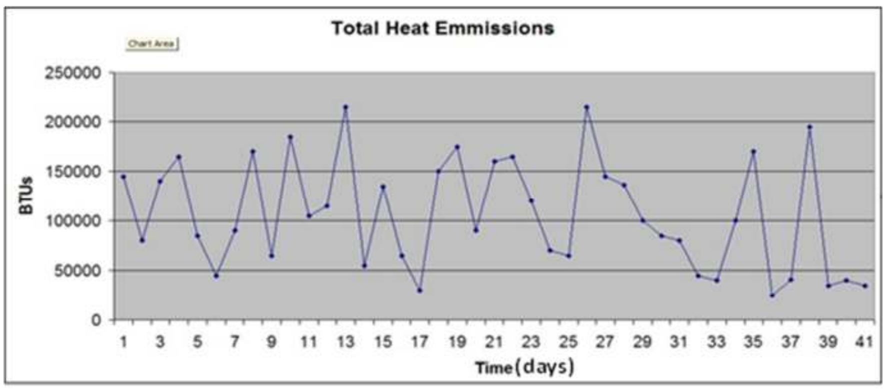


Figure 13: Heat emissions from a simulated shop in Miami.

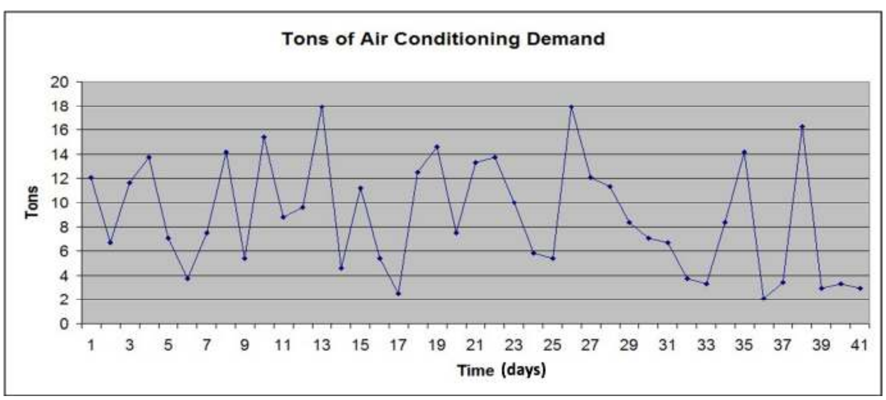


Figure 14: Air conditioning requirements for a simulated shop in Miami.

5 CONCLUSIONS AND FUTURE WORK

This paper describes a process log analysis and simulation-based framework for computing various sustainability metrics in a production environment. By coupling the predictive power of simulation tool for productivity analysis with computation of sustainability metrics, we have created a framework that addresses an important dimension in decision-making namely, accurate estimation of environment impact of designing and operating production and service operations. This approach can be extended to multiple domains and other metrics such as ones related to environment metrics associated with emissions from production devices among others.

REFERENCES

Efron, B. 1979. "Bootstrap Methods: Another Look at the Jackknife." *The Annals of Statistics*, 7:1-26.

Efron, B., and R.J. Tibshirani. 1993. *An Introduction to the Bootstrap*.1st ed. New York: Chapman & Hall.

Rai, S., C. B. Duke, V. Lowe, C. Q. Trotter, and T. Scheermesser. 2009. "LDP Lean Document Production – O. R. - Enhanced Productivity Improvements for the Printing Industry." *Interfaces*, 39: 69-90.

Rai, S., and Lambrecht, C. 2013. "Methods and Systems for Determining Sustainability Metrics in a Print Production Environment." US Patent No 8,619,305, issued May 2013.

Rai, S., and Ettam, R.K. 2015. "Modeling Customer Demand in Print Service Environments Using Bootstrapping". Accepted In *Proceedings of the 2015 Winter Simulation Conference.*

Minnesota Department of Labor and Industry. 2015. " 1999 Minnesota Energy Code Chapter 7678 Thermal Transmittance Calculations and Equipment Efficiencies." Accessed July 15. https://www.dli.mn.gov/CCLD/PDF/energy7678.pdf .

US Department of Energy. 2015. "Building Energy Codes Program." Accessed July 15. https://www.energycodes.gov/.

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