A Dynamic Production Model for Industrial Systems Energy Management

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***Abstract*—Industrial facilities are devoting ever greater attention to the importance of energy in their operations. Consequently, industrial energy management has advanced to include many activities in both planning and operations. Dynamic energy management has evolved as not just an extension of cost-optimal production methods but also in the context of demand side management activities. And yet, the current demand side management literature is inadequate because it does not address the underlying production activities as the existential reason for energy consumption. Therefore, this paper seeks to develop a dynamic production model for industrial systems energy management drawing upon techniques from Axiomatic Design for Large Flexible Engineering Systems and timed petri-nets. The model is applied to an illustrative example to demonstrate the calculation of energy consumption and energy cost curves. This model may be later integrated into conventional industrial systems energy management techniques or into extended demand side management techniques.**

***Index Terms*—Demand side management, axiomatic design, petri net model, manufacturing system, operations control**

I. Introduction

Industrial facilities are devoting ever greater attention to the importance of energy in their operations. Industrial energy consumption makes up for around 33% of the total energy consumption in the United States and many industrial facilities are highly energy intensive [1]. In addition, the reliability of energy supply is often critical to the quality and continuity of many industrial processes (e.g. semiconductor, chemicals) [2].

Consequently, industrial energy management has advanced to include many activities in both planning and operations [3]. Planning, or static energy management, tries to optimize the production system before it has been built, when a new manufacturing line or product is introduced, or when maintenance activities are planned [4]. Operations, or dynamic energy management, tries to optimize the usage of a given set of resources for energy consumption or cost [5]. Changes in customer demand and time-of-use energy prices can be treated as disturbances to which dynamic energy management decisions respond [6].

Dynamic energy management has gained particular importance in the context of electric power grid-balancing activities. The integration of variable energy resources, such as wind and solar energy, has increased the need for controllable loads, using demand side management [7], [8].

Given that many industrial facilities are seeking to implement onsite distributed renewable energy generation as part of corporate social responsibility campaigns, this need continues to grow [9]. An extension of this development is in the implementation of microgrids [10], [11] where industrial facilities with integrated renewable energy can continue to operate even while islanded from the rest of the grid.

And yet, the current demand side management literature is not entirely adequate for industrial facilities. In many works [12]–[14], power loads play a mirror role to power generation; focusing only on the single function of power injection or withdrawal. While the latter exists solely for this purpose, the former draws electricity as a *byproduct* of other activities; be they residential, commercial or industrial [15]. Models that do not capture the dynamics of these underlying activities, especially in the industrial case where competitive pressures are demanding, are inadequate to model and support demand side management decisions.

Therefore, this paper seeks to develop a dynamic production model (DPM) for industrial systems energy management (ISEM). As will be discussed in detail in Section III, the model especially addresses the energy consumption of the resources as a function of the production system state. In addition to the transformative value-adding actions, the model also considers material handling and storage activities as well as the idling and offline state of the resources. The work is developed as an extension and reapplication of the recently published model for a Transportation Electricity Nexus [16], [17]. This model uses Axiomatic Design for Large Flexible Engineering Systems [16]–[28] to model the system structure, and timed petri-nets [29]–[31] to describe its discrete-event systems behavior. These characteristics are appropriate for discrete-part production system which consumes electricity as it transforms and transports product components from raw material to final goods.

The remainder of the paper proceeds as follows. Section II covers the background of Axiomatic Design and petri net dynamics. With this foundation, the model is developed in Section III. This dynamic production model is than applied to an illustrative case to generate simulation results in Section IV. Section V provides a brief discussion of the results and Section VI concludes the work.

II. Background

This section provides the fundamental concepts upon which the dynamic production model for industrial systems energy management is developed. The first subsection introduces Axiomatic Design for Large Flexible Engineering Systems (LFES) [16]–[28] as a succinct way of describing the complete system structure. The second subsection introduces petri nets [29]–[31] as a succinct way of describing the discrete event dynamics of the system behavior.

A. Axiomatic Design for LFES

Axiomatic Design for Large Flexible Engineering Systems Theory has been successfully applied in several large complex (flexible engineering) systems including production, transportation, water distribution, and power systems [16]–[28] . Additionally, it has been used to develop design principles for multi-agent systems in the production and power system domains [26], [28].

Definition 1. Large Flexible Engineering System [19], [21]: an engineering system with many functional requirements that not only evolve over time, but also can be fulfilled by one or more design parameters.

In the context of this work, the *functional requirements* and *design parameters* mentioned in Definition 1 are understood to be *mutually exclusive and collectively exhaustive* sets of the system's processes (P) and resources (R) respectively. This change of terminology is applied consistently for the rest of the paper. Axiomatic Design for LFES is specifically chosen for three specific abilities [19]–[26] that will later directly support energy management:

- to explicitly describe systems of a fundamentally hetero-functional nature.
- to explicitly describe the allocation of system function to system form.
- to explicitly describe systems of variable structure.

Axiomatic Design for Large Flexible Engineering Systems requires the identification of a set of system resources [32]. These are classified as : $R = M \cup B \cup H$. $M = \{m_1, \ldots, m_{\sigma(M)}\}$ is the set of transforming resources, $B = \{b_1, \ldots, b_{\sigma(B)}\}$ is the set of independent buffers, and $H = \{h_1, \ldots, h_{\sigma(H)}\}$ is the set of transporting resources [17]–[23]. $\sigma()$ gives the size of a set and the set of buffers $B_S = M \cup B$ is also mentioned for later application.

Axiomatic Design for Large Flexible Engineering Systems also requires the identification of a set of system process P [32]. They are also classified into three types: transformation, transportation processes, and holding processes.

Definition 2. Transformation Process [19]–[23]: a resource-independent, technology-independent process $p_{\mu j} \in P_\mu = \{p_{\mu 1}, \ldots, p_{\mu\sigma(P_\mu)}\}$ that transforms raw material or work-in-progress to a more final form.

Definition 3. Transportation process [17]–[23]: a resource-independent process $p_{\eta u} \in P_\eta = \{p_{\eta 1} \ldots p_{\eta\sigma(P_\eta)}\}$ that transports artifacts from one buffer b_{sy_1} to b_{sy_2}. There are $\sigma^2(B_S)$ such processes of which $\sigma(B_S)$ are "null" processes where no motion occurs. Furthermore, the convention of indices

$$u = \sigma(B_S)(y_1 - 1) + y_2 \tag{1}$$

is adopted.

Definition 4. Holding Process [19]–[23]: a transportation independent process $p_{\gamma g} \in P_\gamma$ that holds artifacts during the transportation from one buffer to another.

Together, the system processes and resources address the need for hetero-functionality in a LFES.

Axiomatic Design allocates the system processes P to the resources R via the knowledge base J_S in the Axiomatic Design equation [19]–[23].

$$P = J_S \odot R \tag{2}$$

where $\odot$ is matrix boolean multiplication and

Definition 5. LFES Knowledge Base [17]–[23]: A binary matrix J_S of size $\sigma(P) \times \sigma(R)$ whose element $J_S(w, v) \in \{0, 1\}$ is equal to one when action e_{wv} exists as a system process $p_w \in P$ being executed by a resource $r_v \in R$.

Taking advantage of the functional heterogeneity, J_S can be reconstructed straightforwardly from smaller knowledge bases that individually address transformation, transportation, and holding processes. $P_\mu = J_M \odot M$, $P_\eta = J_H \odot R$, $P_\gamma = J_\varphi \odot R$. J_S then becomes [23]

$$J_S = \left[\begin{array}{c|c} J_M & \mathbf{0} \\ \hline \multicolumn{2}{c}{J_{\bar{H}}} \end{array}\right] \tag{3}$$

where in order to account for the simultaneity of holding and transportation processes [23]

$$J_{\bar{H}} = \left[J_\varphi \otimes \mathbf{1}^{\sigma(P_\eta)}\right] \cdot \left[\mathbf{1}^{\sigma(P_\varphi)} \otimes J_H\right] \tag{4}$$

where $\otimes$ is the kronecker product, $\cdot$ is the hadamard product and $\mathbf{1}^n$ is a column ones vector of predefined length n.

The variable system structure is described by the LFES constraints matrix K_S whose element $K_S(w, v) \in \{0, 1\}$ is equal to one when a constraint eliminates action e_{wv} [19]–[23] [1]. Thus, the boolean difference of the LFES knowledge base and constraints matrix give the LFES sequence-independent structural degrees of freedom [19]–[23]. These are instrumental in the construction of the state vector in large complex systems [19]–[23].

Definition 6. LFES Sequence-Independent Structural Degrees of Freedom [17]–[23]: The set of independent actions $\mathcal{E}_S$ that completely defines the available processes in a LFES. Their number is given by:

$$DOF_S = \sigma(\mathcal{E}_S) = \sum_{w}^{\sigma(P)} \sum_{v}^{\sigma(R)} J_S(w, v) \ominus K_S(w, v) \tag{5}$$

[1]Here, it is implicitly understood that K_S depends on time t or the event index k.

B. Petri Nets

Petri nets are a succinct way of describing the discrete event dynamics of a system's behavior [29], [30]. Here, their generic and timed versions are defined.

Definition 7. Marked Petri Net (Graph) [29]: A bipartite directed graph represented as a 5-tuple $\mathcal{N} = \{B_S, \mathcal{E}_S, M, W, Q_B\}$ where:

- B_S is a finite set of places of size $\sigma(B_S)$.
- $\mathcal{E}_S$ is a finite set of transitions/events of size $\sigma(\mathcal{E}_S)$.
- $\mathcal{M} \subseteq (B_S \times \mathcal{E}_S) \cup (\mathcal{E}_S \times B_S)$ is a set of arcs of size $\sigma(\mathcal{M})$ from places to transitions and from transitions to places in the graph.
- $W : \mathcal{M} \rightarrow \{0, 1\}$ is the weighting function on arcs.
- Q_B is a marking (or discrete state) vector of size $\sigma(B_S) \times 1 \in \mathbb{N}^{\sigma(B_S)}$.

The arcs of the petri net graph and its weightings define the petri net incidence matrix.

Definition 8. Petri Net Incidence Matrix [29]: An incidence matrix $\mathcal{M}$ of size $\sigma(B_S) \times \sigma(\mathcal{E}_S)$ where:

$$\mathcal{M} = \mathcal{M}^+ - \mathcal{M}^- \tag{6}$$

where $\mathcal{M}^+(y, \psi) = w(b_y, \epsilon_{\omega v})$ and $\mathcal{M}^-(y, \psi) = w(\epsilon_{\omega v}, b_y)$ and ψ is a unique index mapped from the ordered pair (ω, v).

Note that in this work, the link between Axiomatic Design for LFES and petri nets is established in the shared notation of B_S such that the independent buffers become places, and $\mathcal{E}_S$ such that the structural degrees of freedom become transitions.

The difference between a (generic) petri net and a timed one is established in the state transition function of their discrete event dynamic evolution.

Definition 9. Petri Net (Discrete-Event) Dynamics [29]: Given a binary firing vector $U[k]$ of size $\sigma(\mathcal{E}_S) \times 1$ and a petri-net incidence matrix $\mathcal{M}$ of size $\sigma(B_S) \times \sigma(\mathcal{E}_S)$, the evolution of the marking vector Q_B is given by the state transition function $\Phi(Q[k], U[k])$:

$$Q_B[k+1] = \Phi(Q_B, U[k]) = Q_B[k] + \mathcal{M}U[k] \tag{7}$$

Definition 10. Timed Petri Net (Discrete-Event) Dynamics [30]: Given a binary input firing vector $U^-[k]$ and a binary output firing vector $U^+[k]$ both of size $\sigma(\mathcal{E}_S) \times 1$, and the positive and negative components $\mathcal{M}^+$ and $\mathcal{M}^-$ of the petri-net incidence matrix of size $\sigma(B)_S \times \sigma(\mathcal{E}_S)$, the evolution of the marking vector Q is given by the state transition function $\Phi_T(Q[k], U[k])$:

$$Q[k+1] = \Phi_T(Q[k], U^-[k], U^+[k]) \tag{8}$$

where $Q = [Q_B; Q_\mathcal{E}]$ and

$$Q_B[k+1] = Q_B[k] + \mathcal{M}^+U^+[k] - \mathcal{M}^-U^-[k] \tag{9}$$
$$Q_\mathcal{E}[k+1] = Q_\mathcal{E}[k] - U^+[k] + U^-[k] \tag{10}$$

Note that (generic) petri-nets have transitions of infinitesimal duration while timed petri give them a finite duration. Consequently, timed transitions must essentially be fired once to mark the beginning of their execution with the input firing vector and once to mark their end with the output firing vector. This also requires that timed petri nets track the state of tokens within transitions $Q_\mathcal{E}$ [30], [31].

In practice, the implementation of timed petri nets requires an event list which relates time to moments in which discrete events occur.

Definition 11. Scheduled Event List [29]: A tuple $\mathcal{S} = (u_\psi[k], t_k)$ consisting of all elements $u_\psi[k]$ in firing vectors $U^-[k]$ and their associated times t_k. For every element, $u_\psi^-[k] \in U^-[k]$, there exists another element $u_\psi^+[\kappa] \in U^+[\kappa]$ which occurs at time t_κ d_ψ time units later. $t_\kappa = t_k + d_\psi$.

III. Model Development

Section II provided the fundamental concepts upon which the dynamic production model for industrial energy management is based. This section now directly applies these concepts drawing upon similar work in which Axiomatic Design and petri nets were used to model a Transportation Electricity Nexus [17], [18]. The proposed production system model also includes an explicit description of the state evolution of individual products so as to support mass-customized [23], [24] production. The section concludes with model output functions that describe energy consumption and cost.

A. Axiomatic Design for Production Systems

Axiomatic Design for Production System may be viewed as a special case of Axiomatic Design for LFES. In production systems, the system resources include a set of transforming (value-adding) machines M, a set of buffer locations B, and a set of material-handlers H [23]–[25]. Meanwhile, the system processes as stated in Definitions 2-4 take on production specific meanings of transformational (i.e. value-adding), transportational and fixturing processes [23]–[25]. Note that previous work on axiomatic design for production systems makes sure to define these processes generically and independent of any specific product or resource [23]–[25]. J_S then becomes the production system knowledge base and Equations 2 - 5 are consequently applied. Resource breakdowns, process unavailability and other changes to the production system structure are as captured true elements in the binary constraints matrix K_S.

B. Production System Petri Net

Petri nets have been extensively used to model productions systems [33]–[40]. Traditionally and generally speaking, petri-nets in production systems use transitions to represent transformation and transportation processes. Meanwhile places are used to represent buffers, queues or some intermediate conditions between processes [41]–[44]. More places and transitions may be added to represent control functionality [41]–[44]. The petri-net literature, in providing a very flexible modeling and analytical tool, also gives too much freedom in the modeling process. As a result, there is a great deal of variability in the literature in how a given production system may be modeled as a petri-net, and similarly a given petri-net may be visually interpreted in many ways unless each place and transition is explicitly defined.

Therefore, the production system petri net in this work makes several notable departures from the conventional practice so as to formalize the modeling process and support industrial system energy management. As mentioned in Section II-B, the petri-net adopts its structure from the Axiomatic Design for LFES models. The petri-net places are equivalent to the production system buffers B_S. The petri-net transitions are equivalent to the structural degrees of freedom $\mathcal{E}_S$. Therefore, the convention of indices adopted in Equation 1 *uniquely* defines the petri-net arcs and incidence matrix. The Production System Petri Net is therefore clearly defined as a timed petri net, following Definitions 7, 8, and 10. Note that unlike many traditional works [41]–[44], the application of Axiomatic Design has made storage processes transitions rather than places. This allows "active" energy-consuming storage processes where products may be heated, cooled, or preserved. The rigid definition of places and transitions also leads to an intuitive graphical representation of the petri-net where the production system state is understandable by inspection.

The production system's timed petri net dynamics (Definition 10) are constrained by the production system's capacity constraints and variable structure. Given a capacity vector C_C of size $\sigma(\mathcal{E}_S) \times 1 \in \mathbb{N}^{\sigma(\mathcal{E}_S)}$, it applies a constraint:

$$Q_{\mathcal{E}}[k] \leq C_C \qquad \forall k \tag{11}$$

Rather than change the shape of the petri net incidence matrix, resource breakdowns and process unavailability are similarly modeled with the imposition of the constraint:

$$u_\psi[k] \cdot \left[J_S(\omega, v) \ominus K_S(\omega, v)\right] < C_C(\psi) \tag{12}$$

C. Product Petri Net

One major difference between this production system model and the one developed for a transportation electricity nexus is the explicit inclusion of products as the operand of production processes. The component parts of a product undergo transformations and assembly in a way well defined by the product's structure. To that end, for every product l_i in the product line L, a product net $\mathcal{N}_{l_i}$ is defined [23]–[25].

Definition 12. Product Petri Net [24], [25]: Given product l_i, a product net is a marked petri net graph $\mathcal{N}_{l_i} = \{S_{l_i}, \mathcal{E}_{l_i}, \mathcal{M}_{l_i}, W_{l_i}, Q_{l_i}\}$ where:

- S_{l_i} is the set of product places that represents a product component at a raw, work-in-progress, or final stage of production.
- $\mathcal{E}_{l_i}$ is the set of product events that describe the transformation of the product between product places.
- $\mathcal{M}_{l_i} \subseteq (S_{l_i} \times \mathcal{E}_{l_i}) \cup (\mathcal{E}_{l_i} \times S_{l_i})$ is the product arc relations that describe which products or components receive which product events.
- $W_{l_i} : \mathcal{M}_{l_i} \rightarrow \{0, 1\}$ is the weighting function on product arcs.
- Q_{l_i} is a marking vector that describes the product's evolution.

whose state transition function by Definition 10 is

$$Q_{l_i}[k+1] = Q_{l_i}[k] + \mathcal{M}_{l_i} U_{l_i}[k] \tag{13}$$

D. Coordination of Production System Petri Net & Product Petri Net Dynamics

The production system petri net and product net dynamics are coordinated. This requires a product firing matrix and a product transformation feasibility matrix.

Definition 13. Product Firing Matrix [17], [18]: a binary product firing matrix $\mathcal{U}[k]$ of size $\sigma(\mathcal{E}_S) \times \sigma(L)$ whose element $u_{\psi,l}[k] = 1$ when the k^{th} firing timing triggers a product l to take structural degree of freedom ψ for action.

Definition 14. Product Transformation Feasibility Matrix [24], [25]: A binary matrix $\Lambda_{\mu i}$ of size $\sigma(E_{l_i}) \times \sigma(P_\mu)$ whose value $\Lambda_{\mu i}(x, j) = 1$ iff e_{xl_i} realizes transformation process $p_{\mu j}$.

Consequently, the production system input firing vectors at a given moment k become

$$U^- = \mathcal{U}\mathbf{1}^{\sigma(L)} \tag{14}$$

and each product net firing vector at a given moment k becomes

$$U_{l_i} = \Lambda_{\mu i} \mathcal{U} e_{l_i}^{\sigma(L)T} \tag{15}$$

where e_i^n represents the i^{th} elementary basis vector of predefined length n.

E. Energy Management Output Functions

This subsection defines the energy consumption and cost output functions. The total power $\mathcal{P}_T$ at time k is given by

$$\mathcal{P}_T[k] = C_I^T \left[\bigvee_j^{\sigma(P)} [J_S \ominus K_S]\right]^T + C_P^T Q_E[k] \tag{16}$$

where $\bigvee_j$ is an array-OR, C_I is a vector of size $\sigma(R) \times 1$ defining the power consumed by idling resources and C_P is a vector of size $\sigma(\mathcal{E}_S) \times 1$ defining the power consumption of all structural degrees of freedom above an idle state. Note that the Axiomatic Design's requirement for mutually exclusive and collectively exhaustive production degrees of freedom is entirely consistent with the first law of thermodynamics as a statement of energy conservation. Here, each production degree of freedom including storage explicitly requires a certain amount of electric energy consumption.

The total energy consumption E_T at time k is then

$$E_T[k] = \mathcal{P}_T[k] \cdot (t_{k+1} - t_k) \tag{17}$$

and the total cost of electricity is

$$C_T[k] = C_E[k] E_T[k] \tag{18}$$

where $C_E[k]$ is the time-of-use electricity rate.

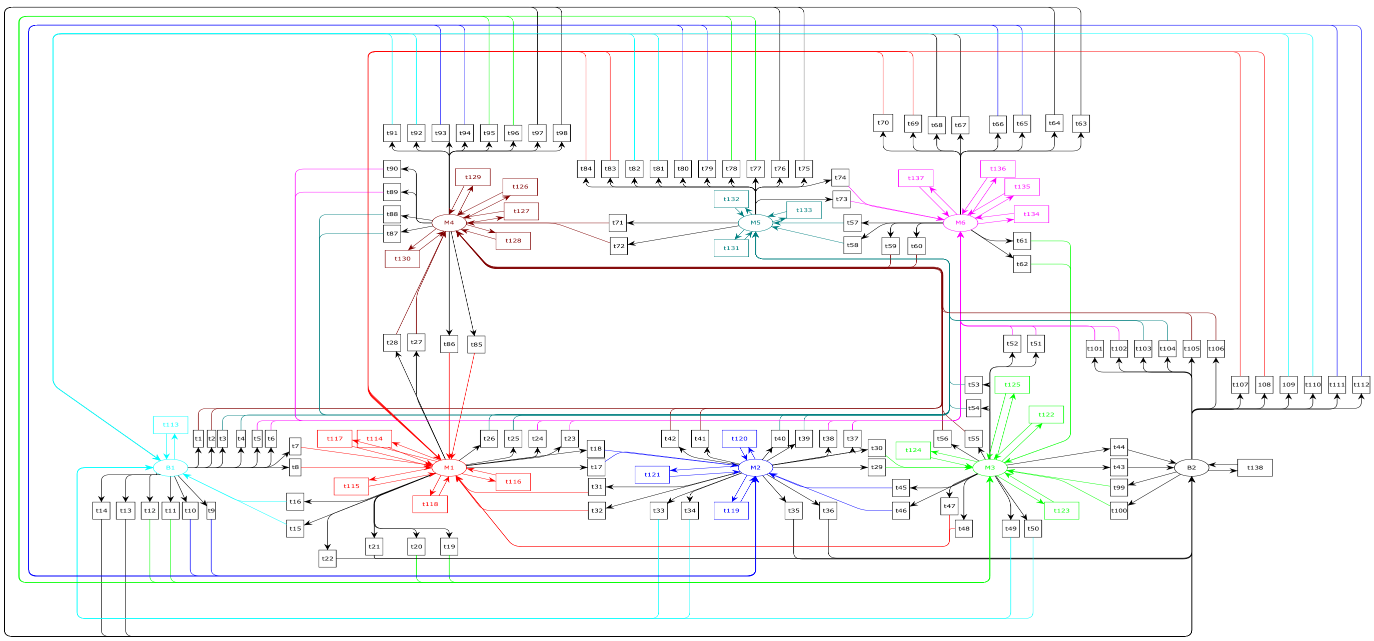

Figure 1: Petri Net Graph of the Starling Manufacturing System.

IV. Illustrative Example

This section demonstrates the dynamic production system model following the method by which it was developed. The first subsection presents an overview of the system. The second subsection defines the production system petri net followed by the product net in the third subsection. The last subsection calculates the energy consumption and cost.

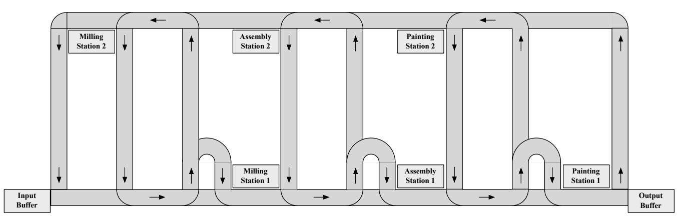

Figure 2: Starling Manufacturing System Overview [24]

A. Axiomatic Design for Production Systems

This work revisits the Starling Manufacturing System which has been presented in several prior works in the context of reconfigurability measurement in automated manufacturing systems [23]–[25]. As a test case, it is of a moderate size and heterogeneity without being overly computationally intensive.

In this version of the Starling Manufacturing System three-components bird feeders are produced. The production system layout is shown in Figure 2. Six transforming machines M are identified: M = {Machining Station 1, Assembly Station 1, Painting Station 1, Machining Station 2, Assembly Station 2, Painting Station 2}, and two independent buffers B = {Input Buffer, Output Buffer}, which makes a total of eight independent buffers B_S. Additionally, two transportation resources are defined, H = {Shuttle A, Shuttle B}.

Next, the production processes are defined. The products undergo seven transformation processes P_μ = {Lathe Tab, Lathe Slot, Mill Hole, Laminate, Paint red, Paint Green, Paint Blue}. The transportation processes occur between the respective independent buffers $P_\eta = \{m_i m_j, m_i b_k, b_k m_i, b_k b_l\} \forall i, j = 1, 2, 3; k, l = 1, 2$. The holding processes account for three fixturing configurations P_γ = {Small Radial, Big Radial, Axial}. The associated knowledge bases have been demonstrated in prior work [23]–[25].

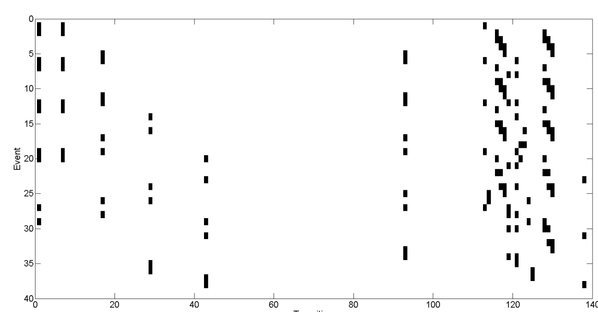

Figure 3: Firing Vectors per Event Timing

B. Production System Petri Net

The production system petri net describes the discrete event dynamics of the production system. Figure 1 shows the Petri Net Graph for this example. The eight independent buffers B_S are represented as places. The transitions represent the production degrees of freedom. The incidence is constructed straightforwardly from Definition 8 or by inspection. Note the petri-net graph in Figure 1 has a highly intuitive structure that corresponds very closely to the production system layout in Figure 2.

A set of input firing vectors were generated for the test case and are taken as given constants. They are represented graphically in Figure 3 as a monochrome image over the course of 139 firing times.

The states of the places Q_B represent the queues in the production system. If a state is larger than zero, the product parts are neither processed nor stored. Ideally, provided there is sufficient storage capacity, queued product parts should be buffered leaving $Q_B = 0$. Figure 4 shows the parts undergoing buffering processes. The remaining transformation and transportation processes alternate between one and zero and closely follow the firing vectors in Figure 3.

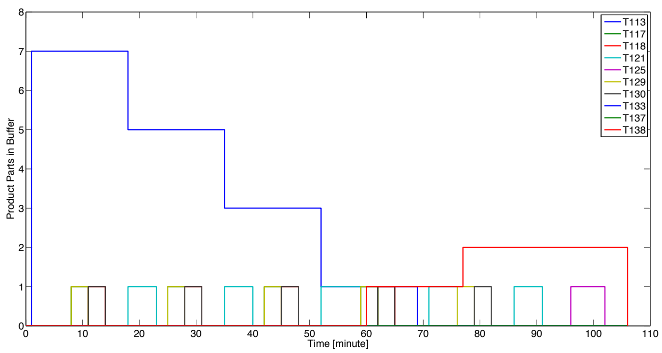

Figure 4: States of the Petri Net Places & Buffering Transitions

C. Product Net Dynamics

The product net introduced in Section III-C keeps track of the production completion of each product as it undergoes successive transformations and assembly processes. The product net for a yellow birdfeeder is shown in Figure 5. The other two products only differ in their final color.

D. Energy Management Output Functions

Using Equation 16 and the fired events from Figure 3, the total power of the production system is calculated and shown in Figure 6. A time of use electricity rate of 14 dollar cents per kWHr was chosen over the time interval from 30-60 minutes and 7 dollar cents otherwise. Consequently, Equation 17 and 18 were used to calculate the final energy cost function in Figure 6.

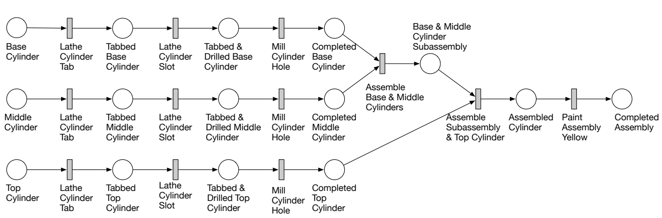

Figure 5: Product net for a yellow birdfeeder [24]

V. Discussion

Analyzing the results, the power consumption over time (Figure 6) has a spiky behavior. This is caused by simultaneously running transformation processes. While transportation processes are rather fleeting, transformation processes are relatively longer. This allows for their comparatively high energy consumption to compound into spikes as product parts arrive at other transforming machines.

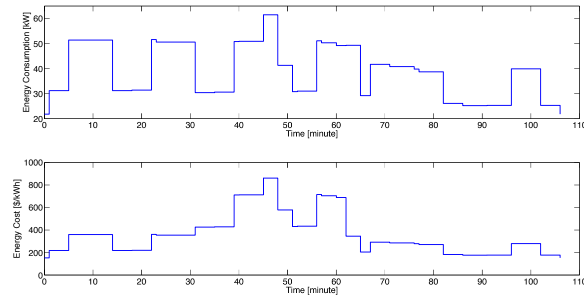

Figure 6: Energy Consumption and Energy Cost results

If the consumption function is combined with the cost function in Figure 6, it can be clearly seen that the costs of energy consumption are magnified during the peak time of use rate. The total cost for the production process is the area under the consumption cost function. The cost can be minimized by shifting timing of the sequence of events. This may result in different firing vectors at a given timing. As the energy consumption shifts, the consumption cost can be manipulated to a potentially lower value. The consumption can also be changed by choosing more energy-efficient resources where their production processes are redundant. Naturally, energy management techniques in the planning phase can serve to reduce the values of C_I and C_P for across-the-board savings in operations.

More generally, the developed Dynamic Production Model for Industrial Systems Energy Management directly links production systems operations to the associated energy consumption and cost. The cost and usage of energy is a direct byproduct of production activities and can be directly manipulated by the startup & shutdown of resources, the choice of more energy-efficient resources, and the shift of production to lower time-of-use rates. In such a way, energy usage can ultimately be viewed as part of the product's bill of material.

The three benefits of Axiomatic Design mentioned earlier in Section II take on greater meaning in the context of energy management. The mutually exclusive and collectively exhaustive production processes and resources lend themselves to precise energy accounting for each production degree of freedom. The differentiation between system function and form allows the choice of more energy-efficient technology when process redundancy exists. Thirdly, the ability to describe a variable system structure allows resources to be turned off for energy savings. Consequently, the evolution of the petri-net dynamics not only shows how and where energy is consumed but also which products have a greater embedded energy.

VI. Conclusion and Future Work

In conclusion, this paper developed a dynamic production model for industrial systems energy management, that uses axiomatic design and timed-petri nets to calculate the energy consumption and cost functions. The energy consumption and cost functions are dependent on the production operations and can therefore be changed by modifying the production scheduling. This offers opportunities for industrial facilities to participate to not just coordinate production and energy management decisions but also participate effectively in demand side management programs.

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