An energy-related discrete event simulation approach

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Abstract **- Discrete event simulation (DES) used to be a decision-making tool with a main focus on cost and time. It's typically used to create dynamic models which simulate a part or the overall manufacturing activity in an effort to optimize productivity and/or cost. In addition to these traditional performance indicators, nowadays, further attention is given to the energy consumption as a key to mitigate the raised energy prices and compensate environmental issues. Therefore, researchers as well as decision-makers are looking for new tools that go beyond the old way of simulating manufacturing systems and address the need to incorporate the energy aspect within DES. As a part of this task, this work aims to integrate the energy consumption modelling to form an Energy-Related Discrete Event Simulation (ERDES) framework. It proposes an operations-based approach taking into account energy effecting parameters relating to all relevant system parts (machines, tools, materials and environment) and their interactions. The case of an injection molding system is presented to illustrate the proposed ERDES framework and to explore its advantages.**

Keywords **- Discrete event simulation, energy modelling, manufacturing system.**

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1 INTRODUCTION

Over the recent decades, energy is gaining prominence and is becoming a major issue especially for energy intensive sectors which see their production costs raising with the electricity price abuses. For such industries, with an energy cost reaching up to 5% of the total turnover. Their energy consumption is as a prerequisite parameter in optimizing expenses. It appears to be a strategic stake, as awareness of this cost and of the environmental impacts that are certainly of no less importance.

The word is facing significant environmental challenges and is requesting a proactive response from the involved parts including the industrial sector which consume around 51% of the total energy consumption being over 266 EJ[3] [1].Thus, companies are no longer responsible of respecting only product quality and deadlines but also seek to meet the emerging industrial criterions including sustainability for environmental benefits [Lee et al., 2014; Oertwig et al., 2015] by own awareness or by the increasing number of legislation on carbon emissions [Henriques et Sadorsky, 2010], imposed energy auditing and standards.

This social awareness both with the heavy financial cost drives research efforts in the direction of reducing energy consumption using different energy saving strategies, to name a few, the use of renewable energies, high efficient motors, smart grid technology, energy conservation and other technics developed for this target.

To achieve this efficiency and to go ahead more environmentally benign manufacturing systems, a good understanding and a fine modelling of energy consumption within the production system is a must. However, modeling energy is not an easy task as the energy consumption within production systems is highly dynamic and needs to be updated depending on the machine states and its interactions with several parameters. To overcome this dynamic, simulation is a promising approach.

The dynamic flow simulation or the discrete event simulation (DES) is a method for anticipating the evolution of complex systems. This method enables creating a digital layout commonly used for manufacturing system design or planning and scheduling operations, real-time control, operating policies and performance analysis [Smith,2003; Negahban et Smith, 2013]. It has been

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[1] http://www.eia.gov/tools/faqs/faq.cfm?id=447&t=1 (last accessed 14.05.15)

proven to be an extremely useful analysis tool and attracted the interest of a large number of researchers for many years as well as software companies. DES software have achieved a significant progress offering more detailed analysis by integrating breakdowns, schedules and other random factors that have a direct impact on production. But today, the majority of these software are unable to combine workflow processes with energy flows and some of them are even unable to incorporate continuously variables as the energy consumed by modelled processes.

This paper is an effort to integrate energy consumption within a DES software. It proposes a structured approach based on operations to supervise energy consumption evolution while simulating a manufacturing activity. It takes into account the different system interactions and energy influencing parameters.

The chosen software offers template development capability to make modeling easier due to configurable multiuse objects. It also has the feature to integrate external programs used to reduce calculation time in case of complex systems. Furthermore, its event-approach allows to update in each stage of the simulation the evolution of continuous state variables enabling an appropriate environment to integrate energy.

The reminder of this paper is as follow: the next section describes previous efforts made on energy modelling and evaluation, and ends with those using simulation. The concept and the methodology of the proposed approach is then described with a brief discussion on the encountered challenges.

An injection molding case study is finally presented to demonstrate the proposed approach explaining the different interactions between system parts and their influence on energy consumption.

2 RESEARCH BACKGROUND

Previous efforts in energy modelling were motivated by the need of manufacturing enterprises to predict and assess their energy consumptions in order to improve their economic benefits and environmental performance [Wang et al., 2013].

It can be seen that in response to the current concern of society, the scientific community is interested, first and foremost, on environmental impacts and are engaged in a daily basis on the improvement of the sustainability performance of manufacturing systems. In this context, [Hauschild, 2005] laid the foundation of the “Life Cycle Assessment” (LCA), which seeks to assess the sustainability performance of a product, including energy consumption. To enhance this effort, some environment-oriented software have been developed. This methodology is often conceptualized within the unit process level. In fact, the research boundary of energy-related works range from the process level to the entire enterprise. Depending on the scale of the system under study, different approaches have been proposed to model, predict and quantify the energy consumption.

Starting from the lowest level, several researchers aimed their works on the unit process level being the smallest component of a manufacturing system. A unit process often corresponds to a unit machine or device which consumes inputs from the techno sphere including energy, raw materials, semi-finished products and other consumables, and generates outputs for both techno and echo sphere in the purpose to accomplish specific mission in the production system [Kellens et al., 2012a]. These works have usually been limited by the availability and the quality of energy-related data. These data could be obtained in different ways from theoretical calculation to real measurements. It is to be noted that predicting energy consumption is not an easy task regarding the complexity and the sophistication of machines and processes.

[Abele et al., 2005] the total energy consumed by a unit process as the sum of the minimum active energy theoretically needed to obtain the physical process, the additional energy needed to compensate losses or to accomplish secondary machine functions and the periphery energy consumed by machine peripherals.

[Kellens et al., 2012a] proposed a LCA-oriented methodology for inventory analysis of a unit process. This work has been developed in the framework of the CO_2PE! Cooperative research program[2]. It proposes two approaches with different levels of detail. The first one, called the “screening approach”, relies on representative, publicly available data and engineering calculations for energy use, material loss, and identification of variables for improvement. The second one or the “in-depth approach” is subdivided into four modules, including a time study, a power consumption study, a consumables study and an emissions study, in which all relevant process in- and outputs are measured and analyzed in detail. In a second part of the same work, the authors presented two case studies to demonstrate the two approaches [Kellens et al., 2012b].

Another relevant methodology to model energy encountered in literature is the Energy Blocks introduced by [Weinert et al., 2011] for planning and operating energy-efficient production systems. This methodology consists on describing the energy consumption of a production equipment according to its operating states, defined as energy blocks. Each energy block is represented by a level of energy required and a duration so that the energy profile of the entire process can be reproduced by a succession of several blocks. The duration and the energy required for each operating state can be fixed or variable depending on different process parameters.

The same principle has been applied to model energy demand for Computer Numerical Control (CNC) machine-tools with dividing, in a second stage, the operational states into further segments by the components in use [Peng et al., 2014]. Thus, the energy blocks or the function blocks, as named in this work, are divided into two sub-types, the machining state functions blocks (MSFBs) and the machine component function blocks (MCFBs).

Efforts done on unit process level can be explored when shifting to the production chain level being the combination of multiple unit processes/machines and their interlinkage. However, the implementation of an energy-based model at the level of a production chain or at the level of the entire manufacturing system require a reliable tool, to overcome the complexity of the energy predicting task and its requirements in addition to the complexity of the production system itself. The more appropriate method to support such model is simulation [Hermann et Thiede, 2009].

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[2] http://www.mech.kuleuven.be/co2pe! (Last accessed 01.05.15)

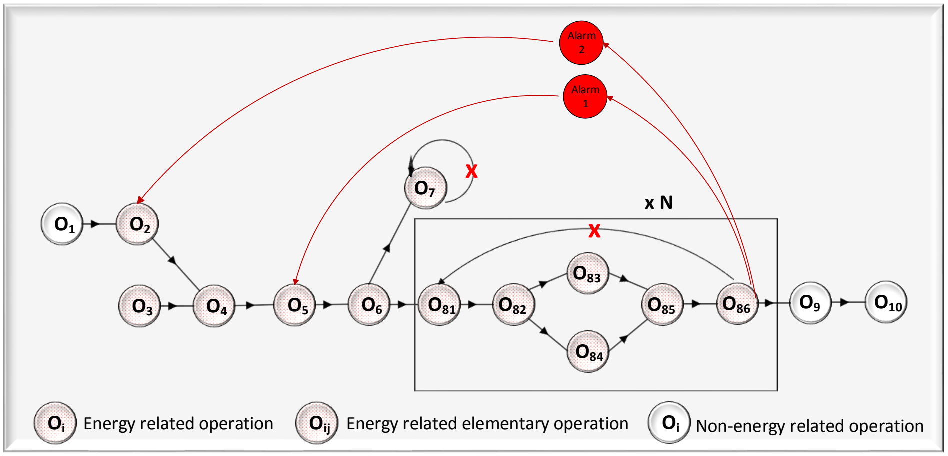


Figure 1. Operations based concept

Several initiatives to couple energy flows with DES could be found in literature but there is still a gap between available commercialized tools, industrial real needs and scientific literature. In this context, [Thiede et al., 2013] conducted a survey on thirteen existing simulation software in order to understand their features and capabilities. The authors introduced then existing environmentally oriented simulation approaches and highlighted the need for further efforts done in this concern.

According to [Thiede et al., 2013], these environmentally related simulation can be classified into three basic paradigms depending on their interfacing with other evaluation and simulation tools. In paradigm A, results obtained from conventional DES tools are integrated in a second step into an external evaluation tool and got converted to environmentally related variables. Paradigms B and C have been proved to be the more appropriate to join energy but each of them still have some weakness. In fact, paradigm B enables more detailed analysis of the whole system with the integration of additional simulation but often leads to quite complex models. In paradigm C, all relevant features are implemented within a single application but the user is still restricted by possible limitations of the simulation environment.

To overcome the weakness of these two paradigms B and C, [Hermann et al., 2011] joined them on a seamless one-stop approach. The authors proposed a highly flexible simulation framework in which they model the whole factory with all relevant energy flows including TBS-related energy flows.

Another work used an energy related simulation model for the analysis and evaluation of energy consumption during the manufacturing phase of a product life-cycle [Rahimifard et al., 2010]. This simulation approach is based on modelling the direct energy (DE) consumed by processes (e.g. casting, machining, etc) and indirect energy (IE) consumed by the plant (e.g. lightening, heating, etc.). Furthermore, DE is divided into theoretical energy (TE) defined as the minimum energy required to carry out a process and auxiliary energy (AE) required by the supporting activities and auxiliary equipment of the process.

Despite these efforts to integer energy into DES models, this is usually a gap between these researches and the industrial need which seek for real commercialized tools joining energy and production flows in the same framework and in a reliable manner. This work aims to integer energy aspect within a commercialized DES software and looks for solutions to make it as more as possible appropriate to deal with manufacturing system complexity and energy challenges. It is to be noted that in the current work we only consider the direct energy.

3 CONCEPT, CHALLENGES AND METHODOLOGY

Responding to the need for more reliability in energy modelling and simulation, a new ERDES approach was developed. This work aims to provide a high flexible tool which will serve as a decision-making tool for more energy efficiency in manufacturing systems. This approach is based on operations related to both production flows and energy flows and seeks to consider all relevant system interactions and energy influencing parameters.

3.1 Concept

In this framework, a manufacturing system could be considered as a set of operations ordered sequentially in series or in parallel with the aim to gain in productivity and profitability while respecting some predefined constraints (e.g. cost, gain margin, environmental compliance, etc.). Each operation could be in turn a combination of several elementary operations repetitive or no (figure 1).

The use of this concept of operations and elementary operations offers high scalability to the model. Thus, one can go so far as the finest detail or in contrast ignores details and go to the most important task. Any system can be modelized with finest details or in a macroscopic way.

According to traditional simulation principles, each operation often requires a machine, a tool, a logistic equipment, an operator or several of them.

According to an ERDES approach, each elementary operation related to machines also requires energy defined by a consumed power rate and a duration that could be fixed or variable. It is obvious that in a manufacturing system there are several types of power but actually we focus only on electric power.

The energy consumed during an operation can then be calculated as the product of the power by the corresponding duration. Thus, energy consumption has to be updated at the end of each elementary operation. We can calculate the energy consumed: by a single machine being a sequence of elementary operations processed by this machine, by product being the

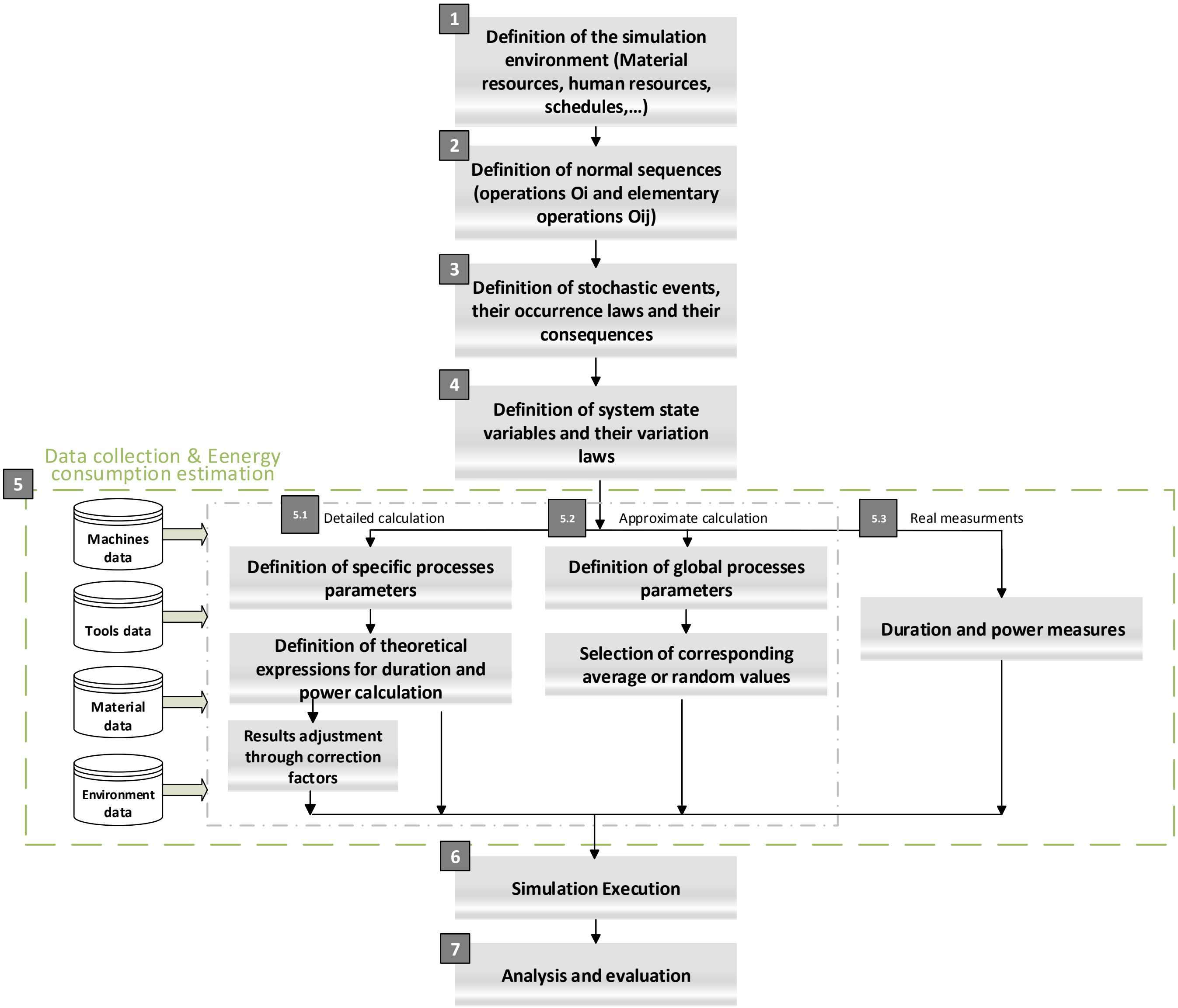


Figure 2. Structured ERDES methodology

sequence of operations processed by specific machines in the product line, or by the whole manufacturing system being a set of sequences processed by all the machines in the plant.

The sequence of these elementary operations is usually predefined by a schedule or by a prescribed process function, and remains unchanged under normal conditions of the manufacturing system. However, a manufacturing system has never been stable and is frequently under internal or external disruptions which interrupt its normal functioning and disturb its operations sequence. These disruptions could be machine, tool, product or even human related incidents and usually occur randomly.

The existence of stochastic phenomena when dealing with a manufacturing system as a whole, and especially when evoking energy aspect, makes the modelling and the analysis of the system more complex and justifies the use of simulation.

As mentioned above, production can be interrupted in an imposed manner (e.g. following machines failures) or in a planned manner (e.g. following breaks, preventive maintenance). This results in sequences interruption and the insertion of non-value added states (idle, failure, standby). Although no value-added operations are processed, energy consumption is still be cumulated during these states (figure 3).

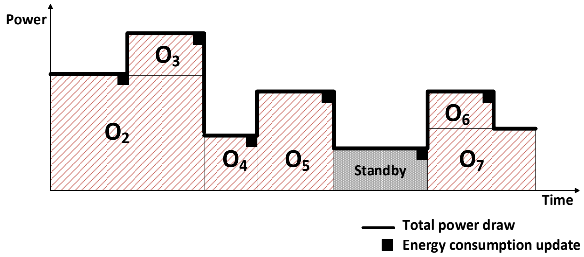


Figure 3. Energy consumption evolution

In some complex manufacturing systems, especially those dealing with thermal flows, some pre-production operations must take place once ahead of production launch in order to meet the necessary and sufficient prior conditions required for a successful production. In such case, production interruptions induce the relaunching of these operations and hence entail further energy consumption.

This consumption depends on the variation of the state of the physical system during these periods of production interruption (more explanations are available in section 5).

The proposed approach takes into account such system interactions and models continuous state variables (e.g. temperature) being energy effecting parameters. These parameters change in a continuous manner according to defined laws of variation as a function of time. The used software allows the integration of continuous model by the introduction of a number of differential and state equations.

3.2 Data collection challenge and remedy

When dealing with such modelling, the most challenging task is data gathering. In fact, the energy-related simulation model reliability depends on the quality and the availability of the energy-related data with different degrees of importance depending on the simulation purpose (e.g. virtual electricity bills, energy prediction, energy efficiency assessment, reorganization, production planning under energy constraints, etc.).

In this goal, dual efforts have to be undertaken: related-power data collection and related-duration data collection to end up with the energy consumption prediction.

These data could be generated through available LCI databases, mathematical models from previous studies and researches, or real measurements.

It is obvious that real measurement is the more appropriate as it provides the more accurate results. However, the problem is that it can be quite difficult and costly in some complex and large manufacturing systems. Thus, one should return to the remedial methods and search into published studies and LCI databases. These databases are mainly used for life cycle assessment (LCA) efforts and offer environment related data including energy consumption that can be exploited in this work.

One of the most recognized and consistent is the Ecoinvent which propose more than 10 000 LCI datasets in different fields of activity. It gives access to the data on unit process level as well as system process level. Furthermore, it provides access to mathematical relations and parameters used to calculate exchanges in the datasets.

Other initiatives for LCI databases have been made by region around the world like the U.S. Life Cycle Inventory (LCI) Database created by the NREL, the European reference Life Cycle Database (ELCD), Korea Life Cycle Inventory (KLCI) database, the Australian Life Cycle Inventory database (AusLCI) and others.

Industry organizations have also made effort to provide LCI databases related to their activities, to name a few, Plastics Europe, American Plastics Council (APC), American Iron and Steel Institute (AISI), European Aluminum Association (EAA), European Copper Institute (ECI), International Iron and Steel Institute (IISI).

These databases are often free, free with contact or license fees especially if used for commercial purpose. They offer an easy and rapid accessibility but the problem is that data are only available for commonly used processes, materials and products.

Nevertheless, a lack of data related to energy consumption may make the model enable. To remedy this, we propose that the end user of the ERDES model can simply introduce energy data if available from one of the approaches mentioned above, otherwise these data can be generated automatically by the model using random samples of data subsets (figure 2).

3.3 Methodology

As can be seen in figure 2, the global structure of the proposed framework starts with (1) defining traditional simulation environment. This consists on a detailed description of the manufacturing system under study including material resources, human resources, work organization and schedules, and all relevant information. A second step is (2) to define normal sequences of operations and elementary operations required to accomplish the production system targets under normal conditions. These sequences respond to precedence constraints imposed by processes or sub-processes and should be respected in the model. This operation based approach allows an easy coupling with production planning programs and enables testing multiple organization of the system under study.

The next step consists on (3) defining stochastic events that can disturb the production activity, their occurrence laws and their consequences. The model user should indicate the consequence of each type of stochastic event on the operations order and on the system state as this has an influence on energy consumption.

Hence, system state variables as well as their variation laws should be defined using differential and state equations (4).

Taking the example of injection molding, a potential production interruption acts upon the state of the physical system (mold and machine temperature) and requires to go back to the preheating operation entailing further energy consumption. This consumption depends on the actual system state (temperature).

Move on modelling specific energy consumption (5), power-related data and duration-related data should be defined by one or several methods discussed earlier depending on their availability.

In a first instance, all energy-related parameters that would be used in the defined theoretical expressions must be introduced (5.1). These parameters could be related to machines (technology, technical data, etc.), tools (material, bulk density, etc.) or products (form, weight, etc.). The results of the theoretical calculation could be adjusted using correction factors (if available) to get closer to reality.

In case of absence of the required data, power and duration values could be randomly selected or filled by an approximately average value depending on the global process parameters (5.2). This solution is proposed to overcome a possible lack of information.

Otherwise, and if the end user of the model want to obtain high accurate results, a measurement campaign of the considered system must be done earlier in order to fill the power and duration data required to turn the simulation (5.3).

Once the simulation executed (6), results about traditional performance indicators as well as energy consumption results can be analyzed and evaluated (7).

4 CASE STUDY- ERDES FOR INJECTION MOLDING SYSTEM

Injection molding is one of the most widely used method of

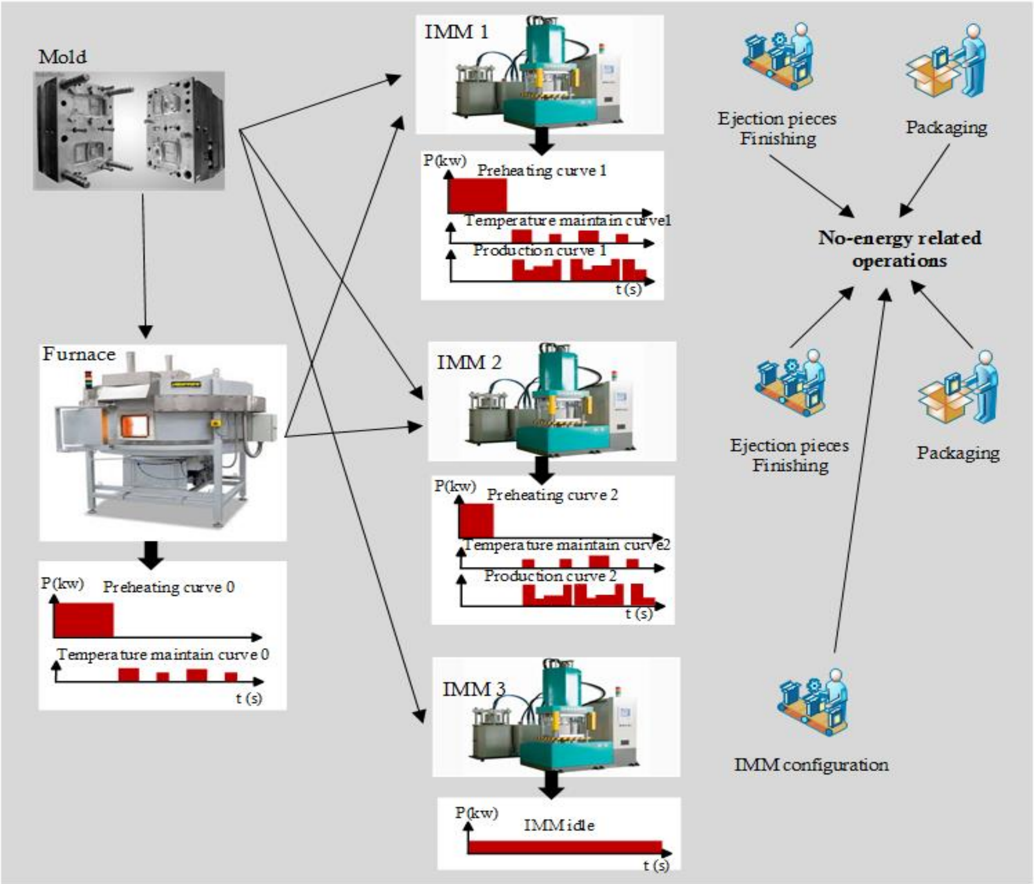


Figure 4. Injection molding workshop

polymer forming. It is recognized to be a very energy intensive process as it requires repetitive operations of heating and cooling. It was the object of several previous energy related researches to predict, benchmark, analyze or improve energy performance [Spiering et al., 2014, Thiriez et Gutowski, 2006; Madan et al., 2014].

In this context, the "ECOTHER" project which is based on a consortium of several French enterprises in the field of polymer forming, has the ambition to provide technical solutions for more energy efficiency polymer forming systems including the injection molding. One of the most important tasks in this project is the development of an ERDES model since the first step for improving energy efficiency is to well understand the energy behavior of the studied system.

As mentioned earlier, modelling energy consumption for such system is quite complex and requires a deep understanding of the processes, machines, tools and their interactions (figure 5) as each of them presents several parameters for energy consumption variation.

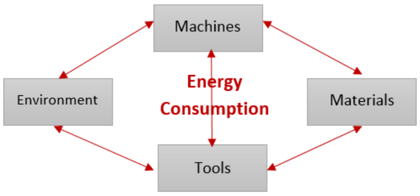


Figure 5. System interactions

This system is mainly driven by the injection molding machines but requires other additional machines as furnaces, take-out machines, finishing machines.

Each machine can carry out several operations. Since these operations require energy, we associate each of them to an energy consumption curve (figure 4).

The superposition of these curve according to the sequence of related operations can provide the global energy profile of the injection molding workshop.

Indeed, a typical sequence of operations starts with an external preheating of the mold within a preheating furnace. This operation is launched in the first instance as a convenient mold temperature is a prerequisite to start the production.

The mold could also be preheated internally into the IMM but this operation can be a bit slow and it would rather make it externally. This operation is proved to be among the more energy intensive operations within the injection molding system. The corresponding energy consumption depends on the maximum power of preheating equipment, the specific heat capacity of the mold, the mold mass density, the target temperature which is a characteristic of the product and the current mold temperature which depends on the ambient temperature (if preheated for the first time or after a production interruption), this parameter presents a system state variable. All these parameter have to be introduced into the model to enable estimating energy consumption in case of absence of real measures.

Concerning the modelling of the IMM and its energy consumption, this proved to be the most complicated task regarding the sophistication of this machine and its dependency on the mold and on the material handled.

Prior to the modelling of the energy consumption of this machine, a deep study on the injection molding process has been done. Then, Preliminary measurements have been made on a hydraulic IMM in order to supervise its energy behavior. It has found that the energy profile of an IMM has the following profile (figure 6).

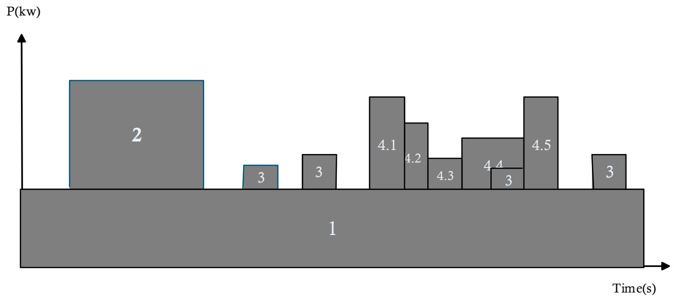


Figure 6. Energy profile for IMM

(1) Once switched on, the machine has a basic energy consumption as computer, fans and drivers start and keep running for the entire time the machine is on.

It is to be noted that this basic energy consumption depends on machines characteristics and technology. In fact, IMMs are distinguished by their drive systems being either hydraulic, electric or hybrid. This parameter has a significant influence on energy consumption and should not be neglected. For instance, if dealing with hydraulic IMM which is managed with a centralized pump, the consumption of drivers is around 50%. Thus, energy consumption should be recorded by the simulation model even during idle and stand by states. This may help the end user of the model to locate energy losses within his system and hence review his organization or even his choice of machines.

(2) Another operation should be undertaken before starting production which is preheating the injection barrel. This device is responsible for melting polymer and must reach a predefined melt temperature depending on the polymer type. This temperature is a parameter for energy consumption and should be indicated when defining energy-related process parameters.

The injection barrel preheating operation is undertaken on full power heating while heaters warm up and until reaching the set point temperature (melt temperature). (3) After that, the process moves to the temperature maintaining operation which is still ongoing while the machine is producing parts and hence the power draw declines.

When dealing with automatic heating devices, energy modelling gets complicated. These devices interact with the physical system state to ensure thermoregulation and hence their energy consumptions become difficult to predict. In fact, the system state depends on the ambient temperature which could not be stable and varies randomly affecting then the energy consumption. For this raison, we propose to use random number generator to model the energy consumption (power and duration) due to the activation and deactivation of heaters in the context of thermoregulation.

Once all required conditions are met, (4) production operation can be launched. This operation can be described as a set of elementary operations presenting a full injection molding cycle starting with mold closing and ending with mold opening. This cycle will be repeated as many times as the required number of pieces is achieved excluding non-conforming parts.

An injection molding cycle is typically modelled by the following elementary operations:

- Mold closing (4.1)
- Injection (4.2)
- Holding pressure (4.3)
- Dosing for the next part and cooling (4.4)
- Mold opening (4.5)

With the proposed simulation framework, the user can detail these elementary operations. For example, mold closing can be further subdivided into mold closing and mold locking with two different levels of power draw.

As indicated earlier, each elementary operation is modeled by a rate of power and a duration and all the complexity stands in the data gathering. Several researches have been done in this light. We have taken advantage to extract some useful expressions to calculate energy required for each injection molding step as well as cycle times [Kalla et al., 2009; Ribeiro et al., 2012; Muller et al., 2014; Madan et al., 2014]. Nevertheless, these expressions merely present theoretical calculations under ideal manufacturing conditions. However, when expecting more accurate results, the end user of the model can introduce correction factors, in case of availability of machines efficiency data, to get closer to reality.

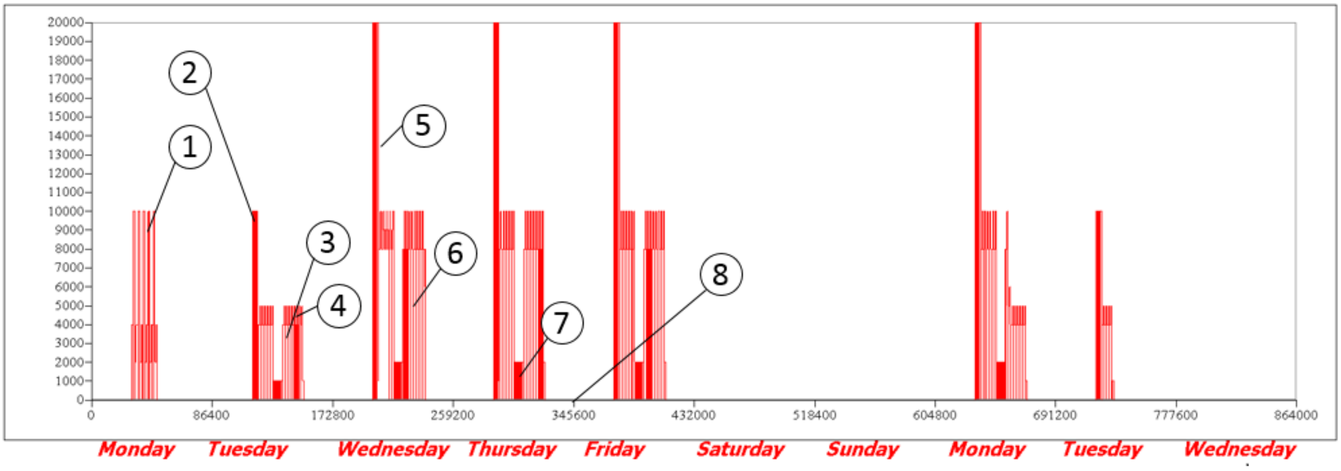
All the operations described above are needed to accomplish a finished product ready for expedition, and are usually carried out in the same order under normal conditions. However, a number of stochastic events has to be considered. In fact, injection molding system often encounters different type of anomalies or incidents related to handled material, mold or machine. These incidents are stochastic events and have to be listed in function of their nature while indicating their law of occurrence and their consequence on the system state and on the normal sequence of operations. For instance, several types of incident can occur to the mold, some of them require a simple and quick intervention of an operator (e.g. cleaning) and hence entails just production interruption while keeping the same system state. However, some much complex incidents can also occur but in this case they require stopping all machine engines or even removing mold. As a consequence, the mold and the injection barrel temperatures (representing the physical system state variables) go down and it is no longer possible to resume production without going back to the preheating operations which are more energy intensive than others. The energy consumption of these operations depend on the value of the actual temperature (a state variable). Hence, the model is in charge of recording these state variables continuously in order to use it in the energy consumption calculation of the next operation if necessary.

We recall that productions interruption could also be scheduled (eg. Break) and also affects the energy consumption.

For these raisons, it is imperative to well handle production interruptions in such systems for more energy efficiency. The ERDES model can be used to compare several production/standby and production/stop strategies.

To validate this ERDES model, we intend to model an injection molding workshop of one of the industries part of the Ecother consortium following the procedure below:

- Gather all information related to production
- Real measures by machine and by module of machine



1 – Preparation of mixtures
2 – Preheating presse 1
3 –Temperature maintain of presse 1
4 – Production with presse 1
5 – preheating presses 1 and 2
6 – Temperature maintain and production with presses 1 and 2
7 – Temperature maintain
8 – Full shutdown during the night

Figure 7. Simulator curve of total energy consumption

- Real measures by group of machines included in the model

We can then compare the real energy consumption curves and those provided by simulation. This validation is not yet achieved due to the difficulty to implement an experimental protocol within a manufacturing system. Nevertheless, a partial validation with two IMMs is done by testing the model using non real data. We have obtained a correct functioning and we have been able to link the energy consumption to the events defined on the process (see figure 7).

5 ACKNOWLEDGEMENT

This work was funded by the BPI ECOTHER project.

6 CONCLUSION AND OUTLOOK

Responding to the need for a best understanding and assessment of energy flows through manufacturing systems, a novel energy-related discrete event simulation (ERDES) approach was proposed. It intends to simulate simultaneously both product flows and energy flows taking into account all system parts interaction like machines, tools, materials as well as the boundary conditions of the productive environment.

The proposed simulation approach offers a high flexibility so that can be applied for any manufacturing system and adjusted to meet end user requirements.

Thanks to its operations based structure, a simple and easy coupling with scheduling programs could be made so one can virtually test his production scheduling under energy constraints like peak surcharges or the applicable electricity tariffs over the day.

Furthermore, this ERDES approach offers a detailed energy supervision and enables a quick locating of system malfunctions and energy losses throughout the production, and hence gives opportunities for more energy efficiency improvement by comparing different strategies (eg. production/standby, production/stop, etc).

To defy energy-related data challenges, multiple methods to fill it within the model are possible.

Depending on the availability of these data as well as the level of comprehension of the handled processes and systems, the current ERDES framework also provide high versatility offering to the end user the opportunity to go so far as the finest detail or in contrast ignore details and go to the most important task.

Although this framework deals with a number of very important issues concerning coupling energy with production flows simulation, it is still limited and further efforts should be done to incorporate technical Belding Services consumption, conveying and transportation devices consumption and all relevant energy consumption within a manufacturing system, to the ERDES framework.

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