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Procedia CIRP 29 (2015) 92 – 97

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The 22nd CIRP conference on Life Cycle Engineering

Hierarchical modelling of complex material and energy flow in manufacturing systems

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Abstract

Over the past decades, the economic and environmental soundness of manufacturing systems are often questioned because of the large consumption of energy and primary materials. In order to investigate potential opportunities towards achieving the material and energy efficiency in these systems, it is essential to model these flows and associated complexity in detail. An isolated consideration of individual processes which in themselves are comprised of sub-processes is not a sufficient approach. To obtain a reasonable level of detail from the system, hierarchical structure of energy and material consumers in the system is required.

In this paper a simulation based approach is presented to model energy and material flows. This approach considers hierarchical structure of energy and material consumers within the system. It can be served as a base to identify hotspots and to assess the effectiveness of retrofitting exercise through what-if scenarios. An industrial case study is used to demonstrate the applicability and the validity of the proposed approach.

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Keywords: Energy and Material Efficiency, Simulation, Hierarchical Modelling, Retrofitting, Manufacturing Systems

1. Introduction

Manufacturers today face many challenges to stay in the business. The trend among the manufacturers is now to seek opportunities to improve the efficiency of the material and energy and shift to environmentally benign practices. Some of the major forces that drive this shift are: steady increase in costs of energy and resources, risks associated with availability of material and energy, government regulations in reducing the environmental impacts of production.

Most of manufacturing systems involve complex, dynamic systems which consume energy, water and raw materials. Inefficiencies in these systems result in excess consumption of resources leading to increased costs and environmental footprint. Through an understanding of these inefficiencies, improvement opportunities can be identified and strategies can be developed to effectively lower costs and carbon footprint. In general, improvement opportunities and practices with respect to material and energy consumption within manufacturing systems can be generated over a wide range from a single machine to an entire factory. Some of these opportunities may involve adaptation of a new technology or retrofitting of the machine components [1] and [2]. Some other improvements focus on operational level and involve resource conscious production, and multi-objective process planning [3] and [4].

In order for management to decide what improvement strategies to initiate and at what scale and organisational level, it is first essential to understand the system inefficiencies and characteristics of the responsible elements in relation to material and energy usage. Common practice for the evaluation of the material and energy efficiency is through detailed breakdown and modelling of the energy and material usage within a manufacturing system. Few techniques and frameworks have been introduced for modelling the energy flows and associated environmental and economic impacts

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doi:10.1016/j.procir.2015.01.023

within the manufacturing systems [5], [6], and [7].

From the organization of the manufacturing systems perspective, manufacturing activities can be considered as being composed of at multiple levels[8]. It is also important to note that the choice of system abstraction levels depend on the goal of the research and on the specific question it addresses. Within the literature [9] and [10] focused on unit process levels and energy load profiles of single machines. There also exist several examples of process chain level modelling with reference to cumulative load profile of all the machines [11]and [12].

Environment-oriented software tools have been developed through the years in support of environmental impact studies. Life cycle assessment software tools like Umberto® are used in modelling the hierarchical structure of the material and energy flow. These tools allow for material and energy flows to be viewed from department level down to an individual process level. While simple top-down account of system's input-output flows is essential- as a starting point for modelling the aggregated flows in the entire system- the hierarchical modelling is still prone to limitations. They lack the ability to model the dynamic and complex systems. Because of the static nature of the existing LCA methods, the complex interdependencies between the hierarchical levels and time dependent flows cannot be captured. Some researchers have developed simulation models to address the time dependency and complexity of the energy flows and the associated environmental impact in the manufacturing systems. [13] utilises LCI (Life Cycle Inventory) data and performs static calculation of environmental metrics on the simulation results; therefore dynamic environmental assessment is still not achieved.

The emphasis of this paper is particularly on evaluation of the manufacturing system performance and the impact of machine component change and retrofitting. Current modelling efforts consider the horizontal interaction between machines and their corresponding dynamic flows or at best consider vertical and dynamic interactions between levels but with not enough details. Obviously there is a gap in literature for dynamic evaluation of the improvement strategies on the machine component level in relation to different levels of the manufacturing system's hierarchy. Therefor this paper proposes a hierarchical system modelling method through simulation. In section 2, the modelling framework and associated simulation model are presented. The applicability of the proposed model is verified through an industrial case study in section 3 followed by what-if-scenario exercise through simulation. In section 4, the simulation results and future work will be discussed.

2. Hierarchical simulation modelling of energy and material flows

The approach proposed in this paper is an extension of the previous framework reported by [14].As mentioned in previous section , the system break down in modelling manufacturing systems is highly motivated by the goal of the study. In order to fulfil the requirements of the current study on machine retrofitting, an additional level (Component Level) to the previous framework is considered. On this base, this paper proposes a hierarchical framework for modelling energy and material flows within manufacturing systems in four levels (Figure 1).

A bottom- up approach in the modelling of the manufacturing system starts from the bottom of the hierarchy. First the unit process level which represents the individual machine is characterized and modelled. Since the machine is a complex system in itself and consists of sub-components, further decomposition is applied on the machine level that results in the modelling of the component level. Thus machine component level is embedded within the unit process (machine). By linking the unit processes; process chains on the third level are composed. In multi-product manufacturing systems, different products can have different process chains and follow different routing.

The top of the hierarchy - Factory level - the technical building services such as compressors, central cooling and other departments responsible for production planning & control are modelled. The bottom up approach integrates the energy and material input-output flows within lower abstract levels to the upper levels. The controls and improvement strategies are propagated from Factory level to sub-ordinate levels.

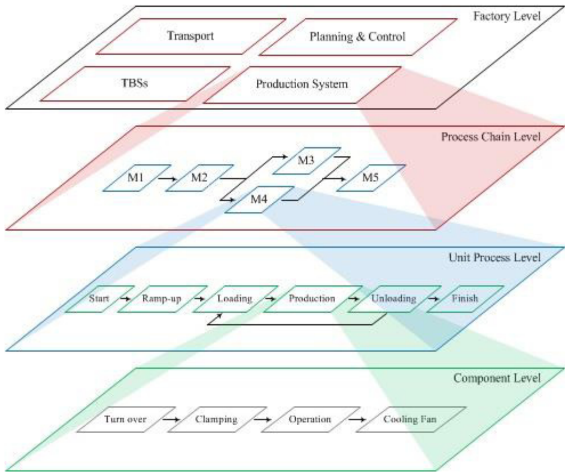


Figure 1 Hierarchical modelling framework [14]

3. Simulation model

A simulation model was developed in Anylogic®. Anylogic is a simulation program by XjTek using a subset of UML for Real Time (UML-RT) as a modeling language platform. The model of the whole factory is constructed following the bottom-up approach. Generic module of a single machine (unit process) is developed. The unit process module uses state-based modelling technique and considers different operational states. The component level is also embedded in this module. The process chain and the whole factory models are built upon the unit process module considering the configuration of production facilities.

3.1. Unit process and component level model

Basic unit process modules to represent machines are created by using state charts. One special characteristic of the state charts is that they are based on petri-net. Through petri nets, system's architecture, stepwise processes and hierarchy can be modelled and graphically visualized. Event- and time-driven behavior of the unit processes and their dynamic energy and material consumptions are modelled using different Operational States and Transitions. In this paper, seven Operational States are defined with each state consuming different amount of energy and auxiliary material as shown in Figure 2 (a). The definition of each state is as the following:

- Off: refers to the state when the machine is switched off at the end of the production shift.
- Change over: refers to the state when the machine is being set up for producing a different product, e.g. tool changing.
- Ramp Up: refers to the period after switching on the machine tool- the acceleration of the main motors before the actual production. Normally results in a power peak.
- Preproduction: refers to the period when the placement and clamping of the part or work piece on to the machine is performed followed by machine tool positioning.
- Production: refers to the state when the machine is processing the material and producing desirable products, normally considered as the value-adding period.
- Postproduction: refers to the state when the machine's auxiliary equipment is activated after the main Production; e.g swarf fan, entry/exit run out tables and metal choppers.
- Failure: refers to the state that the machine fails to produce products and requires repairs or maintenance.

The machine goes to different Operational State following prompts dictated by Transitions. In other words Transition decides how long the machine should stay at each operational state or under which circumstances machine can switch from one operational state to another.

By correct parameterization of the states, dynamic flow of the material and energy to and from the machine is approximated. For each operational state, an average value for the power is used. In addition to the choice of a constant value for the machine's power, other methods are also used. For example [15] used a mathematical equation based on the empirical models to configure machine's operational states for power and time.

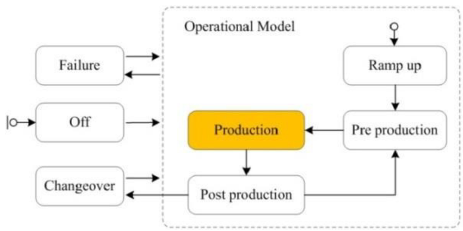
Parts are processed according to a defined machine cycle time. At the arrival of an entity (part) into the machine's buffer, the machine goes through different stages before processing the part: preproduction and tool positioning. These activities are considered as non-value adding but these are predecessors of the actual value adding activity. Production can only start after non-value adding activities finish. When the production of the first part is finished, the machine's post production state is activated. The machine at this state also consumes energy and auxiliary; these consumptions are also non-value adding. The component of the machine such as main drive motors, pump, and hydraulics are also configured using state chart Figure 2 (b). With the state chart technique, cooling system and its components are decomposed to its sub-systems. Hence the component levels are configured as sub-states for the defined main states which are named 'composite states' in Anylogic®.

3.2. Process chain and Factory level

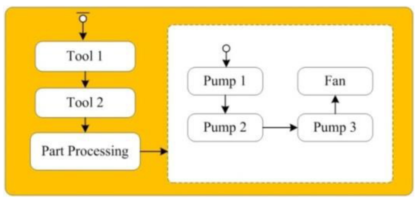
After configuring each process, the processes are connected to each other in special orders according to process chain configuration. In order to represent the entire factory, previously configured TBS modules like air compressors [16], Boilers [17] transportation and of course the production planning and control (PPC) modules [18] are dragged and dropped into the process chain's main worksheet in Anylogic (see Figure 3). The PPC module contains the customer orders, auxiliary materials master data, production jobs, bill of materials (BOM), product routings, and production batches.

4. Case study

In order to underline the potentials and actual applicability of the proposed simulation model, an aluminum recycling and rolled sheet production facility is investigated. Three main departments are involved for the entire production of the aluminum rolls: Ingot, Hotline, Canstock. Each department is responsible for a chain of processes and sub-processes. In Ingot department firstly scrap aluminum is melted in rotary furnace and the impurities removed. The melted scrap aluminum together with virgin aluminum are melted and cast into 10 tones ingots. After the casting, the rough surfaces of the ingots are milled off. In hotline department, ingots are milled down to 2-3 mm width and are formed into coils. In the Canstock department, coils are further milled to the required width and cut into customer specifications.



(a) Unit process level



(b) Component level

Figure 2 Different operational states of the unit process

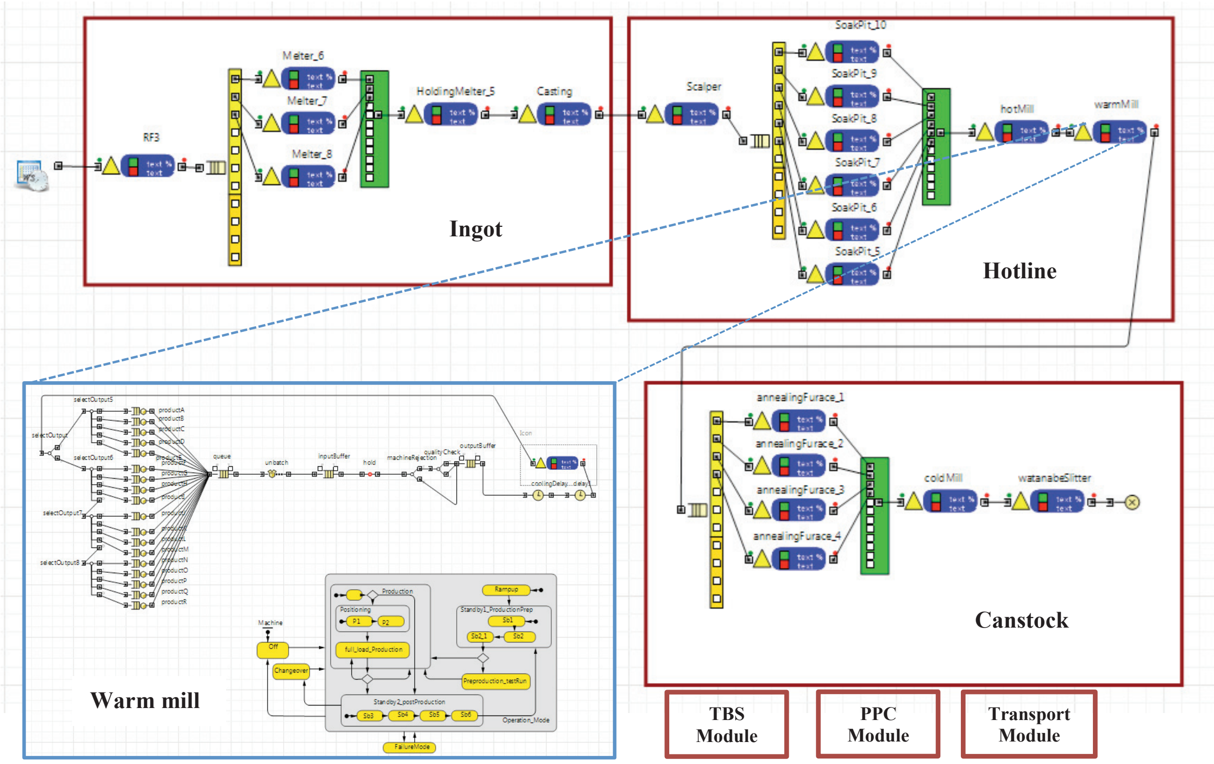


Figure 3 Overview of simulation worksheet in Anylogic showing the different modelling modules

Factory-level simulation model is developed considering the entire three major departments, their processes and TBS. Ingot and Hotline departments each consist of 4 process steps and Canstock involves 3 process steps.

There is a choice of 3 melters for melting process and 6 soaking pits with different capacity. The required data on process parameters (cycle time, change over time, failure rates) and production parameters (production rates, material usage, material recycling rates) are separately obtained from SCADA (supervisory control and data acquisition) and enterprise resource planning database (ERP). The size of the processes with nominal power measuring in unit of MW prohibits accurate electricity metering thus the consumption rates are estimated values.

The simulation on this level depicts all the relevant input-output flows and interconnections between departments, provide vital information such as exact location and root cause of big consumptions of material and energy within the entire factory. From the results the most energy intensive department among all others is identified to be the hotline department. Further analysis on the hotline department energy consumption showed that the warm mill process in particular is the most energy consuming process with the share of 41.21% of the total consumed energy (Figure 4). With our focus on Warm mill as the hotspot, a detail break down of its energy consumption and the contributing elements was carried out.

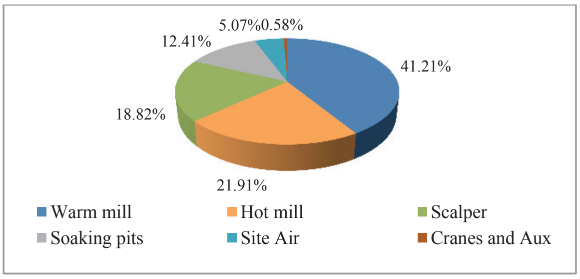


Figure 4 Hotline department energy consumption break down

Hot aluminum coil from upstream process (Hotmill) arrives into the Warm mill's Stand where the value adding activity (the milling) takes place. The aluminum coil is further milled by the rollers multiple times to achieve the required thickness. At the end of the Stand there is the trimmer, which planes the coil edges before it is coiled up by the belt wrapper. All of the sub-processes are supported by a separate coolant system and hydraulic systems. The analysis on the simulation results on the unit process level explicitly showed the top two biggest contributors to the warm mill electricity consumption are the stand and the coolant system (Figure 5). 47% of the energy consumption of the Warm mill occurs in the stand during the actual milling process. The main motor of the stand has a nominal power rate of 5 MW. Due to budget restrictions, changing the main motor was not practical.

Therefore the second most energy consumer was nominated for more detailed analysis. The following details the mechanism of the coolant system and characteristics of its relevant energy and material flow:

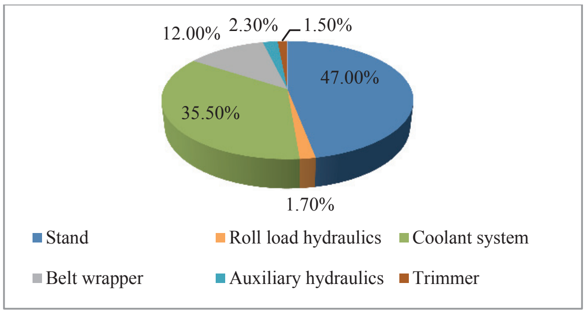


Figure 5 Warm mill process energy consumption break down

Throughout the milling process the cooling is required. During the milling process which takes about 15 min, the coolant is pumped up from the tank and sprayed on to the aluminum sheet. The used coolant fluid gets filtered and pumped back to the main loop again. There are 8 different pumps and 2 cooling fans involved in the cooling process on the component level. Due to chemical and biological stability of the coolant fluid, the coolant fluid has to circulate constantly. To maintain the required circulation the entire coolant system including pumps is found out to be running 24/7._After careful_examination of the machine in different modes of operation and stand by, it was also found that not all pumps are technically needed in the circulation of the fluid. Only 2 circulating pumps with nominal power of 55 kW each are responsible for the circulation, meaning the rest of the pumps and cooler fans can be switched off when the mill is not in operation.

Motivated by the result of the analysis on this level, the management decided to evaluate retrofitting of the coolant system. One option in particular was adding an automatic switch control on the six pumps. The control switch will turn off the pump when its function is not required.

4.1. What-if-scenario

The entire factory was simulated for duration of one month as the baseline scenario with the coolant system in operation 24/7._The effect of possible improvements through additional control switches is evaluatged through simulation of a “what-if” scenario.

In the retrofitting scenario, six automatic control switches were virtually applied on the six pumps. In theory it means if the milling process is not in action the motor load factor of the pumps and the cooler fans is reduced to 0. The impact of adding the switches was calculated on the Coolant system, Warm mill, Hotline and on the entire factory.

The simulation results on energy savings were very promising (Table 1). On the component level alone there is 80% improvement on energy reduction which can translate into 11% reduction on the entire factory energy consumption.

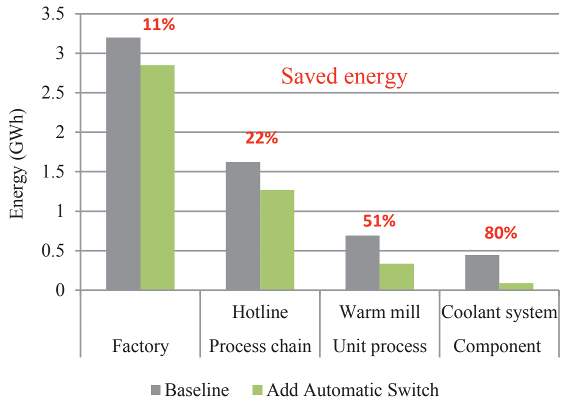


Table 1 Energy saving – effects on hierarchical levels

A cost analysis report based on the simulation result on provision of purchasing 8 control switches is presented to the top management. The report points out the obvious gains the requisition decision would bring to the entire company and to all the sub-divisions involved. The gains are definitely not limited and restricted to economic performance of the company but also considerable improvement on environmental performance of the company can be expected.

5. Summary and Outlook

Opportunities for improvement of energy and material consumption in manufacturing systems are many. These improvement plans come from different hierarchical levels and impact the entire manufacturing system and also sub-systems. In order to investigate potential opportunities toward the efficiency of material and energy in manufacturing systems, the energy and material consumptions and sources of waste need to be tracked down.

Although a number of commercial tools have been utilized to track and monitor energy and material use in a factory and across various process chains, the detailed breakdown of energy consumption within unit processes and their components and its attribution to total energy requirement of the entire factory is not well understood.

Moreover in typical cases of manufacturing organizations, performing any sort of analysis on material and energy flows requires support from the databases of ERP systems and the SCADA-System. With an integrated simulation platform it is possible to directly derive material and energy flow data and use as input data. In this paper simulation modelling of the manufacturing systems and their sub-systems in a hierarchical manner is proposed. This paper highlights the need for greater transparency of energy and material consumption across manufacturing processes and outlines a modelling framework to represent the hierarchical and vertical interrelations between different levels involved in the manufacturing system.

The proposed hierarchical simulation model and its applicability are studied through a case study. With the proposed approach, evaluation of the improvement strategies on energy and material efficiency was investigated. Further to this in order to achieve global optima and see the impact and effect of the improvement implementation on different abstraction levels simultaneously, further work is recommended.

Acknowledgement

The authors would like to acknowledge Australian Research Council (ARC) and the industrial partner for supporting this research project.

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