An Extended Energy Value Stream Approach Applied on the Electronics Industry

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Abstract. In today's manufacturing companies lean production systems are widely established in order to address the traditional production objectives such as quality, cost, time and flexibility. Beyond those objectives, objectives such as energy consumption and related CO2 emissions gained relevance due to rising energy costs and environmental concerns. Existing energy value stream methods allow the consideration of traditional and energy related variables. However, current approaches only take the energy consumptions of the actual manufacturing process and set-up times into account neglecting non-productive operational states and technical building services related consumption. Therefore, an extended energy value stream approach will be presented that provides the necessary degree of transparency to enable improvements of the energy value stream of a product considering also the influence of product design parameters.

Keywords: energy value stream mapping, sustainable manufacturing.

1 Introduction

The rising environmental awareness in society as well as worldwide increasing prices for natural resources and energy impose higher pressure on the manufacturer of goods than ever before. During the last 20 years an increase in energy prices of up to 100% has been recorded in Germany [1]. To cope with these cost advantages, companies have to identify measures to lower their energy consumption while maintaining their throughput. To accomplish the challenge of identifying and reducing the energy consumption within the production environment, the principles of the lean management have been adapted and extended towards this topic and a "lean and green" philosophy has been developed. From a methodological perspective the value stream mapping has been extended in order to identify the main energy consumers in a production line – the energy value stream mapping [2], [3]. In this paper the printed circuit board (PCB) manufacturing will be used as a case study for the methodological developments. PCBs are used in most electronic devices. The manufacturing of PCBs is a complex and energy intensive process. As about 88% of the worlds PCBs production is situated in Asian countries and only approximately 5% of the production located in Europe [4], this imposes a high cost pressure on the PCB producers in Europe.

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A possible cost reduction can be achieved by reducing the energy demand of the production system. While there has already been done a comprehensive research work on recycling of PCBs [5], [6] as well as in terms of life cycle assessment for PCBs and PCB using products [7], [8] the energy consumption aspects in the PCB manufacturing have not been addressed so far.

2 Background

Manufacturing processes transform inputs into value-added outputs. Energy consumption is a physical necessity to perform that transformation. Gutowski et al. have shown in early studies that the actual consumed energy for machining processes is exceeded by the energy demand for related auxiliary processes like coolant pumps, lubrication supply and technical air ventilation [9], not mentioning the indirect energy drawn by technical building services such as heating, air conditioning or air suction. Additionally, Devoldere et al. are stating that in energy assessments of manufacturing processes the time aspect cannot be neglected. Specific time studies have shown that less than 13% of energy expenditures have been utilized for productive operations [10]. This clearly indicates the need to approach the assessment of energy demand of production systems by considering also the dynamic behaviour of machines. As depicted in Fig. 1, the dynamic load profile of a manufacturing process can be broken down over time by energy analysis, clearly stating, that all defined operating states of the given process are varying in their mean power demand, timing and therefore also in their energy amounts (indicated by the shaded areas).

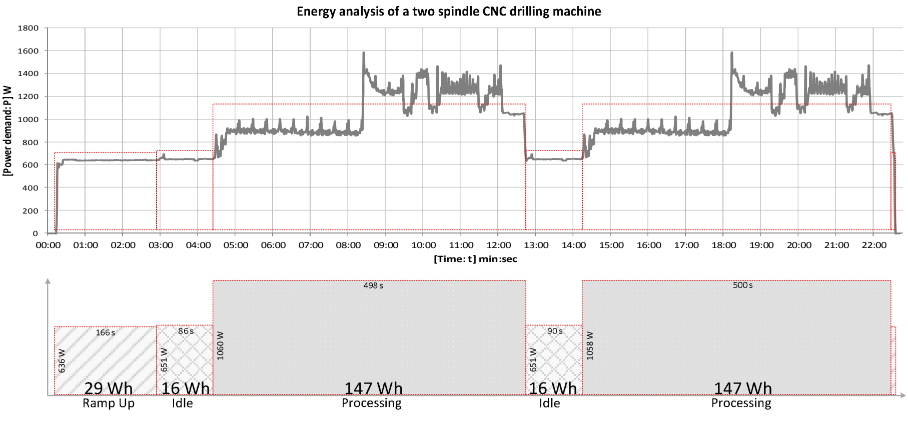

Fig. 1. Electrical load profile of a drilling process broken down into productive and non-productive energy shares

To cope with these dynamic energy demands, a suitable assessment of energy performance can be applied as proposed by Zein [11]. And feedback using key performance indicators (KPI) can be given. One effective way to assess the energy demand of production lines is a tool adapted from lean production. The *energy value stream mapping* (EVSM) is an extension of the lean production tool *value stream mapping* (VSM). VSM is utilized to analyse and prioritize sources of waste as listed by Womak and Jones [12] in order to enable future process improvement efforts through eliminating them by a continuous improvement processes. Extending methods for *value stream mapping* are presented by several authors. The U.S. Environmental Protection Agency (EPA) has given a recommendation to enhance the widely known lean process data by process specific energy use data [13]. Erlach and Westkämper are proposing a rather more detailed assessment of process energy. Next to the lean process variables the calculated energy intensity (EI) of the specific process [2] is displayed. In terms of lean KPI, both methods are using similar syntax and structure. While, the EPA is giving recommendations to include energy usage data without clearly stating how to ascertain the energy intensity KPI, Erlach and Westkämper are clearly allocating the mean energy demands of the processing state to the main energy carriers of production environments (electrical power, compressed air volume flow and gas volume flow) and giving them a common physical unit of measurement (kW) in order to allow an easier comparison. The common KPI for energy intensity (EI) is calculated by Erlach and Westkämper by summing up all mean power demands of the process specific energy carriers and multiplying this sum with the specific customer takt time and the number of resources [2]. The idle time of the processes is considered indirectly in the EI indicator. A drawback of this is the lack of visibility of the impact of the unproductive and productive time shares in matter of energy intensity as well as the influence of supporting processes from technical building services side. As shown earlier in Fig. 1, the power demand for idle states (non-productive) and processing (productive) can differ significantly. Additionally, the influences of product design parameters on the process design and scheduling are not represented in current approaches, as they represent the basis for a truly co-evolving energy-aware product and process design. Therefore, an approach is needed that is able to differentiate between different states of a production process and is able to indicate influences from product design perspective in order to truly derive hot spots of energy intensity and trigger improvement measures into the right direction.

3 Concept

Fig. 2 shows the conceptual framework of the extended energy value stream mapping approach. In a first step, the basic procedure is similar to the (energy) value stream mapping approaches mentioned above - from the perspective of one product (family), it is necessary to identify related processes and collect relevant data on time and energy related indicators. However, three innovative characteristics are introduced here:

Dynamics of Energy Consumption (A)

As indicated above, the pure consideration of single (average or nominal) values in energy value stream mapping impedes a closer look into composition of consumption and, thus, the derivation of improvement potentials for all relevant forms of energy. Therefore, the proposed approach distinguishes between three different machine states: ramp-up, processing and idle. The necessary data is being obtained through power measurements which provide power (P) profiles of the considered processes, respectively machines as shown in Fig. 1 exemplarily for a drilling process. Besides the power for ramp-up, idle and processing also the necessary time (t) values can be directly derived from the measurement as shown. The proposed method takes into account a specific production scenario in order to derive the necessary time values.

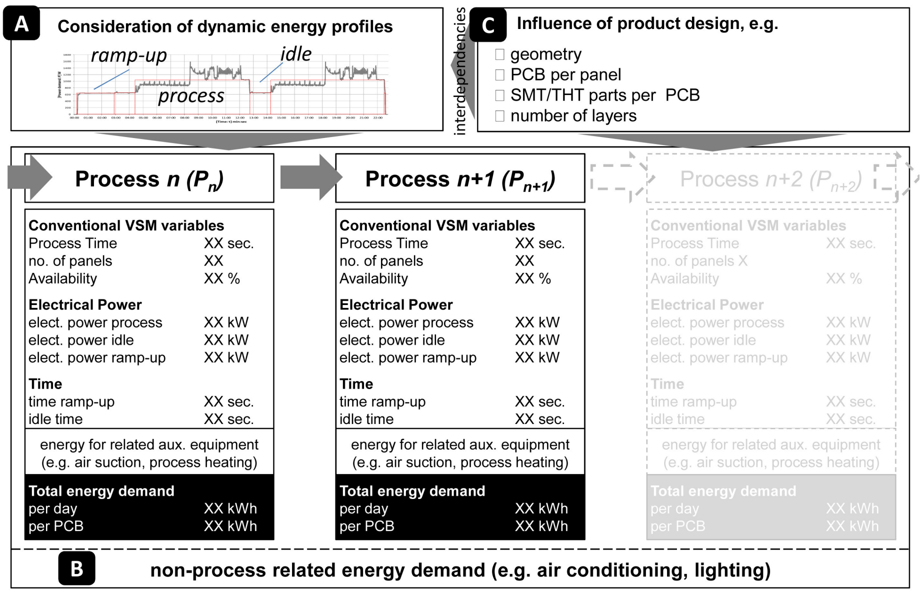

Fig. 2. Conceptual framework of the extended energy value stream mapping approach

As indicated in equation (1) the base is an available production time (e.g. per day) in which the machine can basically be used for production.

Through subtracting the calculated daily ramp-up time (number of ramp-ups per day multiplied by single ramp-up time, see equation) and processing time values (number of products multiplied by single processing time, see equation), a good estimation of idle time per day can be derived.

$$t_{idle} = t_{day} - t_{rampup} \times n_{rampup,day} - t_{process} \times n_{products,day} \quad (1)$$

Integration of Further Relevant Consumption Portions (B)

In general, manufacturing process chains are embedded within a factory system which includes technical building services (TBS). TBS are not value adding in itself but provide necessary forms of energy and media (e.g. compressed air generation, coolants) and conditions (e.g. lighting) for enabling production [14], [15]. They can sum up to a significant share on energy demand of manufacturing companies, but were not considered in energy value stream mapping so far. Within the proposed extended EVSM approach TBS related energy demand can be either considered as

- related to specific processes respectively machines (e.g. air suction), or as an
- energy overhead with relevance for the whole process chain.

This distinction is made based on the technical circumstances but also depending on data availability while often a process specific breakdown is simply not available with reasonable effort. For the first case this indirect energy demand is directly added to the energy demand of the specific processes (TBS*). In the second case the energy demand of the TBS is equally distributed over all products within the considered time frame. The necessary energy demand rate and the time value for the specific TBS system is obtained through measurements or estimations. According to all those influences, e Conceptual framework of the extended energy value stream mapping approach quation (2) shows the calculation of the energy demand for the defined period of time. For the specific energy consumption, this value is divided by the amount of produced units within this timeframe.

$$E_{products,day} = \sum_{all,energies} \Big(P_{TBS} \times t_{TBS,day} + \sum_{all,processes} \big(P_{process} \times t_{process,day} + P_{rampup} \times t_{rampup,day} + P_{idle} \times t_{idle,day} + P_{TBS^*} \times t_{TBS^*,day} \big) \Big) \qquad (2)$$

Consideration of Product Characteristics (C)

Product design may have significant influence on manufacturing energy demand since already in the design phase necessary processes and partly also process parameters are determined. However, besides few publications for the case of metal machining (e.g. [16], [17], [18], [19]) just little work has been done to systematically address those interdependencies so far. Some tools provide environmentally related information to product designers already, but this information is mostly related to, e.g. used materials or recycling issues. Against this background, the proposed approach consciously integrates product related issues in energy value stream mapping. Therefore, for each process it is questioned to which extend the energy demand is influenced by product design characteristics. This paper specifically focuses on printed circuit boards (PCB) - in this case the amount of PCB layers (single-sided, double-sided or multi-layered), the PCB geometry in terms of size (how many PCB fit in one panel) and the number of electronic parts (separated according to SMD and THT parts) are relevant product related parameters. Whereas design parameters are mainly related to later functionalities of the product, the proposed approach provides manufacturing related information to the designer in order to create cost- and eco-efficient product designs.

4 Application

The extended EVSM method was applied exemplarily for the real case of a PCB value chain consisting of a PCB manufacturing and PCB assembly company, covering 46 sequential processes. In the selected scenario, the available production time per day is ten hours, the availability is assumed to be 100% and only one product type is produced. The maximum number of panels (products) per day is limited by the capacity of the bottle neck process. Since some processes can handle several panels at once, the bottle neck is not necessarily the process with the longest processing time. It is further assumed that no parallel process equipment is available and that the production system is in steady state. For each process, energy and time related parameters were determined and the energy demand was calculated. The process related indirect energy demand for air suction and compressed air and light was added to the process' energy demand if allocation was possible. Otherwise the indirect energy demand is summed up to the energy overhead of the process chain. In Fig. 3, the approach is exemplarily shown for the processes drilling and reflow soldering (the load profiles of

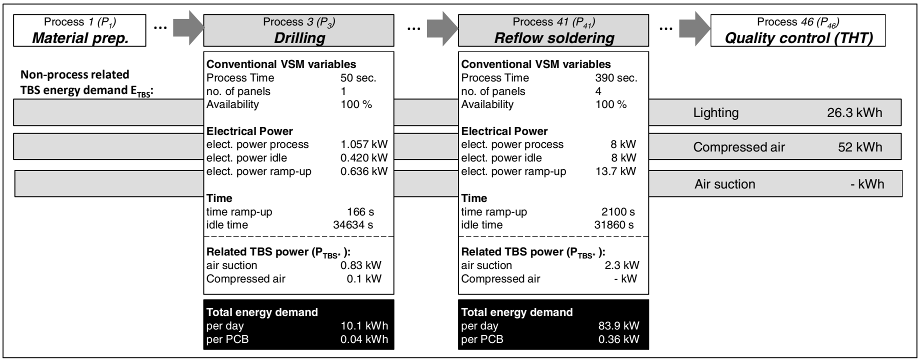

Fig. 3. Exemplary Extended Energy Value Stream Mapping for drilling and reflow soldering

the drilling process is shown in Fig. 1) for the fabrication of single-sided PCB with 50 SMT and 50 THT parts.

Drilling has a processing time of 50 seconds for one panel and reflow soldering requires 390 seconds for four panels, hence 97.5 seconds per panel. The total energy demands of the drilling process and reflow soldering process for one PCB are 0.04 and 0.36 kWh respectively. However, the energy consumption characteristics of these processes differ. While the power demand of the CNC drill is 1.06 kW during processing and 0.42 kW during idle, the reflow oven demands 8 kW constantly. Further indirect energy usage for air suction and compressed air is caused by the drilling process while 2.3 kW of energy demand for air suction is related to the reflow soldering process. Knowledge about these differences in energy consumption of production processes is important for the derivation of improvement measures. Therefore Fig. 4 presents the energy demand for each operational state of all 46 processes as well as for related TBS. It shows that several processes cause high energy consumption during idle mode. These processes with long idle times and high power demand during idle mode should be subject for production management, e.g. the energy consumption could be reduced by different scheduling strategies such as batch production.

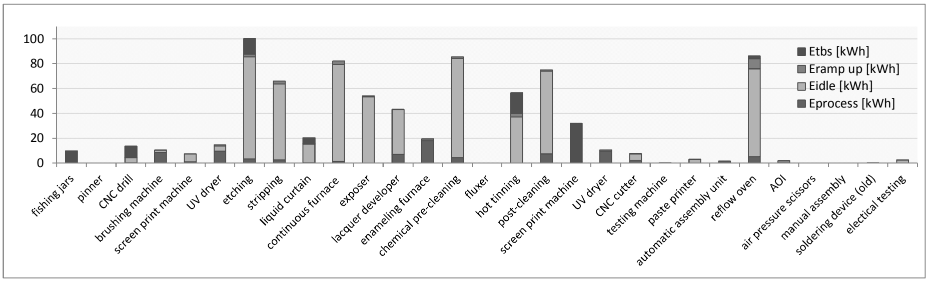

Fig. 4. Energy demand of each operational state and TBS of all 46 manufacturing processes

Besides specific energy consumption profiles of the processes, the influence of product properties on energy consumption is considered. For double-sided or multi-layered PCBs extra processes are required compared to single-sided PCBs; some of

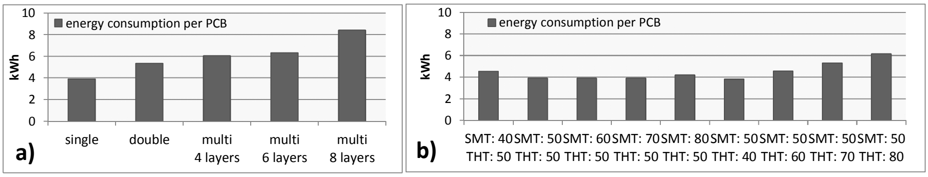

Fig. 5. Energy demand for one PCB for single-sided, double-sided and multi-layered boards with four, six and eight layers (a) and for different numbers of SMT and THT parts (b)

them also need to be repeated for each additional two layers. Thus the utilization of these processes as well as the energy consumption increases with the number of layers. The energy demand per PCB for different types of PCBs is shown Fig. 5a).

Further, the process times for the assembly of SMT and THT parts on the board increase with the number of parts. While the SMT assembly is performed by a machine the THT parts are manually mounted. The analysis shows that the total energy consumption is not increasing significantly with an increasing number of SMT or THT parts due to the low energy demand of assembly equipment. However, with a higher number of THT parts the THT assembly becomes the bottle neck process and the energy consumption per PCB increase due to a reduced output of PCB, as shown in Fig. 5b). The energy demand per PCB also depends on the number of PCBs per panel (ranging from 3.8 to 6.2 kWh), which is restricted by the geometry and size of each single board.

5 Summary and Outlook

Altogether the extended energy value stream is a powerful method which takes into account more realistic circumstances and provides valuable information for both manufacturing engineers and product designers. It gives very clear indications about the composition of energy demand according to all relevant subsystems of the factory and the different operation states of involved equipment. Based on this detailed analysis, a specific derivation of technical and organizational improvement measures becomes possible. The application of the approach further shows the influence of certain product properties on the energy demand of the production system. This information can be used during product development in order to evaluate design options regarding the trade of between higher production cost (due to energy consumption) and development effort. It is also the ideal base for product related cost or carbon footprint calculations. Future work will focus on the validation of the method on different production scenarios in other industries. Moreover the results of the case study indicate the importance of the co-evolutional development of product design and production system. Therefore the relevant dependencies have to be investigated and new ways and tools for the coordination and communication need to be established.

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References

1. http://www.bmwi.de/BMWi/Navigation/Energie/Statistik-und-Prognosen/Energiedaten/energiepreise-energiekosten.html# (last access: July 03, 2012)
2. Erlach, K., Westkämper, E.: Energiewertstrom – Der Weg zur energieeffizienten Fabrik. Fraunhofer Verlag, Stuttgart (2009) ISBN: 978-3-8396-0010-8
3. Shahrbabaki, S.A.D.: Green and Lean Production Visualization Tools - A Case Study exploring EVSM. Master thesis work, Mälardalen University (2010)
4. World PCB Production Report for the Year (2010) ISBN: 978-1-61193-500-4
5. Wang, X., Gaustad, G.: Prioritizing material recovery for end-of-life printed circuit boards Original Research Article. Waste Management (2012) (in Press)
6. Guo, J., Xu, Z.: Recycling of non-metallic fractions from waste printed circuit boards: A review. Journal of Hazardous Materials 168(2-3, 15), 567–590 (2009)
7. Taiariol, F., Fea, P., Papuzza, C., Raffaella Casalino, R., Galbiati, E., Zappa, S.: Life Cycle assessment of an integrated circuit product. In: Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment, pp. 128–133 (2001)
8. Kanth, R.K., Wan, Q., Liljeberg, P., Zheng, L., Tenhunen, H.: Comparative Study for Environmental Assessment of Printed and PCB Technologies, Joukahaisenkatu. TUCS General Publication Series, pp. 978–952 (2010) ISBN: 978-952-12-2497-3
9. Gutowski, T., Murphy, C., et al.: Environmentally benign manufacturing: Observations from Japan, Europe and the United States. Journal of Cleaner Production 13(1), 1–17 (2005)
10. Devoldere, T., Dewulf, W., Deprez, W., Willems, B., Duflou, J.: Improvement Potential for Energy Consumption in Discrete Part Production Machines. In: Proceedings of 14th CIRP Conf. on LCE, pp. 311–316 (2007)
11. Zein, A.: Transition towards Energy Efficient Machine Tools. Springer Verlag, Heidelberg (2012) (pending for publication) ISBN 978-3-642-32246-4
12. Womack, J.P., Jones, D.T.: Lean Thinking: Banish Waste and Create Wealth in Your Cooperation. Harper Business (2003) ISBN 0-7432-4927-5
13. US EPA: Lean, Energy & Climate Toolkit: Achieving Process Excellence Through Energy Efficiency and Greenhouse Gas Reduction, EPA-100-K-07-003 (2007)
14. Hesselbach, J., Herrmann, C., Detzer, R., Martin, L., Thiede, S., Lüdemann, B.: Energy Efficiency through optimized coordination of production and technical building services. In: 15th CIRP International Conference on Life Cycle Engineering, Sydney, pp. 624–629 (2008) ISBN 978-1-877040-67-2
15. Seow, Y., Rahimifard, S.: A framework for modelling energy consumption within manufacturing systems. CIRP Journal of Manufacturing Science and Technology 4(3), 258–264 (2011)
16. Narita, H., Fujimoto, H.: Environmental burden analysis due to high speed milling. Presented at the 19th International Conference on Production Research (2007)
17. Nawata, S., Aoyama, T.: Life-cycle design system for machined parts - linkage of LCI data to CAD/CAM data. Presented at the Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 299–302. IEEE Comput. Soc., Tokyo (2001)
18. Seow, Y., Rahimifard, S.: Improving Product Design based on Energy Considerations. In: Hesselbach, J., Herrmann, C. (eds.) Glocalized Solutions for Sustainability in Manufacturing, pp. 154–159. Springer, Heidelberg (2011)
19. Thiede, S.: Energy Efficiency in Manufacturing Systems. Springer, Heidelberg (2012)